Damage assessment of an ancient fort in India

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ABSTRACT

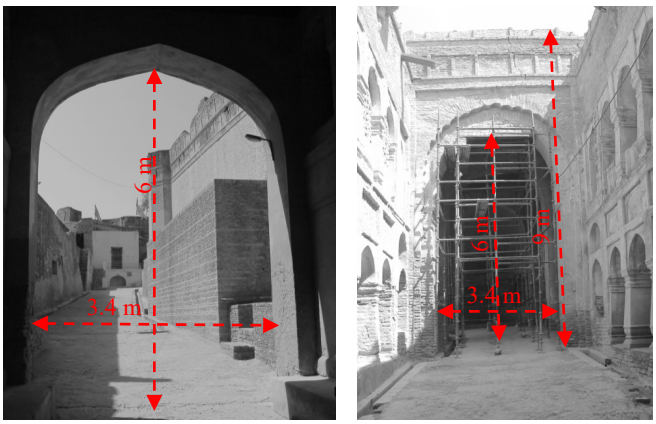
The historical fort of Bhatner at Hanumangarh, Rajasthan in India was built around 1700years ago using burnt clay bricks with lime mortar. This fort complex has three gateway adorned with arches and tri-arch colonnaded spaces.These gateway structures are significantly distressed and several cracks on arches and vaults of gateway possibly are observed. The current paper presents a detailed geotechnical and structural investigation to find out the root cause of the distress in the fort. For geotechnical Investigation, the methodology followed for the geotechnical test comprises of appropriate sub- soil exploration including field investigation at 4 bore hole locations and relevant laboratory tests on soil samples for determining allowable bearing pressure of the soil. In structural investigation, settlement analysis has been performed on the 3D Finite element model of the fort considering gravity load and earth pressure on the fort wall using TNO DIANA software package. The study concludes that the distresses shown on the structure especially at Gateway 2 and 3 are due to soil settlement.

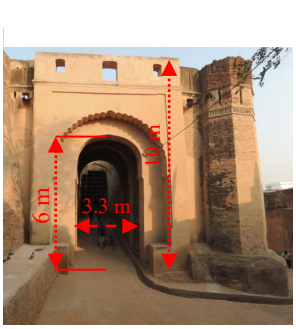
Keywords: masonry structure; 3D FE analysis; settlement; pore pressure

1 INTRODUCTION

The fort of Bhatner at Hanumangarh finds its mention in travelogues as a prominent place in the old Multan- Delhi trade route. The old name of Hanumangarh was Bhatner which means “the fortress of the Bhati Rajputs". The fort of Bhatner is built in burnt bricks and it covers an area of approximately 52 bhigas. The origin of fort dates back to 1004 AD (same era in which Muhamad Ghazni attacked India). The fort actually stands on a high mound, the lower levels of which revealed prehistoric remains. The fort is large parallelogram having 12 projected circular bastions on each sides. The fortification walls also function as retaining walls of the mound on which the Fort is built. This fort complex has one gateway which is one the southern side. This entry point comprises of series of gateway. The gateway near to *Nagarpalika* road can be termed as Gateway 1 , one near Hanuman temple can be termed as Gateway 2 and subsequent one as Gateway 3 (Figure 1-2). The gateways are adorned with arches and tri-arch colonnaded spaces. The structural system used arches in brick masonry, brick vaults and lime concrete terracing. Lime mortar is used in construction. The central space inside the fort complex has presence mound with archaeological remains. The Bhatner fort structure is constructed of masonry walls in burnt clay bricks with lime mortar. The most prominent structure within the Fort walls is the gateway. This gateway structure (especially between gateway 2 and 3) is significantly distressed and possibly affected by differential ground settlement. This structural is compromising the safety of adjoining structures as well as the users of this space. All arches in gateway 3 along with the vault roofs and terrace shows signs of distress. The current paper presents a detailed geotechnical and structural investigation to find out the cause of the distress in the fort.

Figure 1. Gateway 1 (L) and Gateway 3 (R)





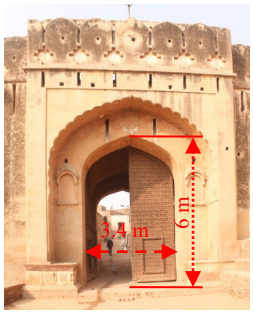


Figure 2. gateway 2 (L) and gateway 1 (R)

2 METHODOLOGY

To develop a strategy for conservation a thorough condition assessment of the structure and analysis is essential. A detailed condition assessment was prepared based on the architectural documentation drawings. This gave an evaluation (quantitative and qualitative) of the decay of the elements. The information sourced from this evaluation is used in the numerical analysis of the entire structure using finite element model (FEM). A geo technical investigation was conducted to analyze the properties of soil. The methodology followed for the geotechnical test comprises of appropriate sub- soil exploration including field investigation at 4 bore hole locations and relevant laboratory tests on soil samples for determining allowable bearing pressure of the soil. The information sourced from this evaluation is used in the numerical analysis of the fortification wall and bastion.

3 CONDITION MAPPING

The condition mapping is an important exercise in which the distress and decay observed on the structure is mapped. The condition mapping exercise was carried out on the gateway structure especially gateway 2 and 3. The prominent distresses that were identified are cracks on arches and vaults, rising dampness and cracks on the terrace. Following are the detailed observations:-

(A) Cracks on arches and vaults of gateway 3: Arches are structural systems which are highly sensitive to any lateral movement of the support of the arch. Such movement compromises the line of compressive forces (or thrust) which keeps the arch together and resists superimposed loads. Lateral movement of supports induces tensile stresses along the cross sections of the arch and masonry subsequently develops cracks in these sections as the tensile strength of masonry is very low. The prominent crack on the roof indicates significant structural movement causing cracks in horizontal structural system. The distressed rea is provided with temporary steel props.

(B) Cracks on terrace of gateway 3: A diagonal crack has been observed on the terrace surface of gateway 3. This crack can be correlated with crack observed on arches and vaults below.

(C) Cracks on arches of gateway 2: A similar pattern of cracks can be observed in gateway 3 is visible in gateway 2. It is also a resultant of the lateral movement of the support of the arch.

(D) Rising Dampness: Another prominent issue observed that the structure is severely affected by rising dampness from the ground and from moisture retention in upper portion due to inadequate rainwater discharge from terrace of the structure.

4 STRUCTURAL INVESTIGATION

Settlement analysis has been performed on the 3D Finite element model of the fort considering gravity load and earth pressure on the fort wall. Figure 3 demonstrate different view of the model. Finite Element analysis was carried out using TNO DIANA software package. The fort was modeled with solid tetrahedron element TE12L which is four-noded three-sided isoparametric element. It is based on linear interpolation and numerical integration. The basic variables of these solid elements are the translations u_x, u_y and u_z.

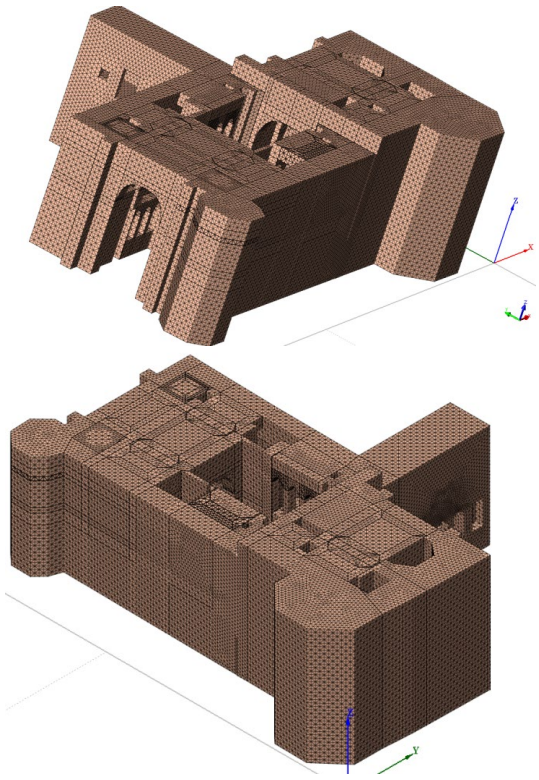
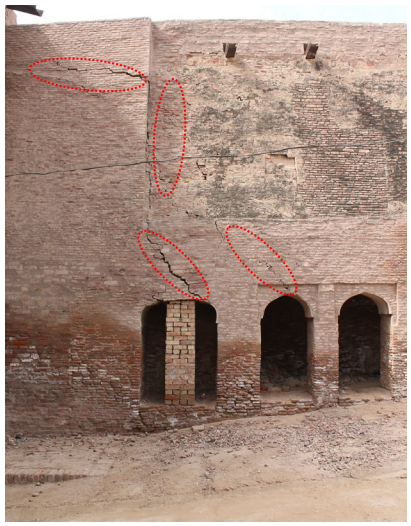


Figure 3. FEM Model of the gateways

The walls were considered fixed at bottom. The vaults and openings in the walls were modeled according to the geometry.



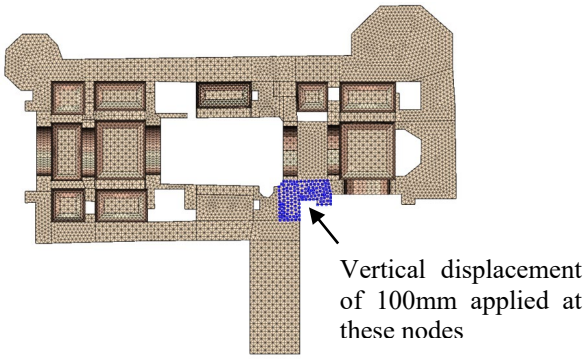


Figure 4. Deformed wall section in elevation and plan

Figures 4 show the walls with maximum settlement as noticed during the site visit. All restraints were removed from the bottom most nodes of these walls and vertical displacement of 100mm have been applied at those nodes. To simulate the platform beside the bastion wall, nodes at the side of the wall upto the height of the platform were considered fully restrained in all directions.

The principal stress distributions in the critical section are shown in figure 5 It is evident that the tensile cracks were formed near the opening (Figure 5) and in arch (Figure 6) due to soil settlement.

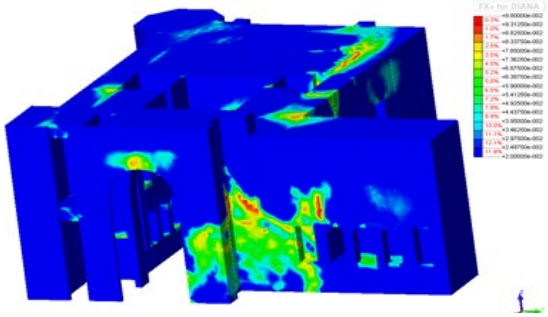


Figure 5. Mean principal stress distributions

5 GEOTECHNICAL STUDIES

In order to assess the stability of the existing fort wall, a numerical analysis was conducted. Detailed information regarding the cross section of the brick masonry wall and the foundation details are not available. The measurements of the brick masonry wall used in the analysis were approximated from the observation made during the site inspections showing the exposed section of the collapsed bastion wall. The wall dimensions and the foundation soil layers used in the analysis are shown in Figure 6. The curtain wall between the rounded bastion walls was analyzed with a soil slope in front of the wall. There were no details on the slope and height of the soil fills in front of the curtain wall and hence was assumed.

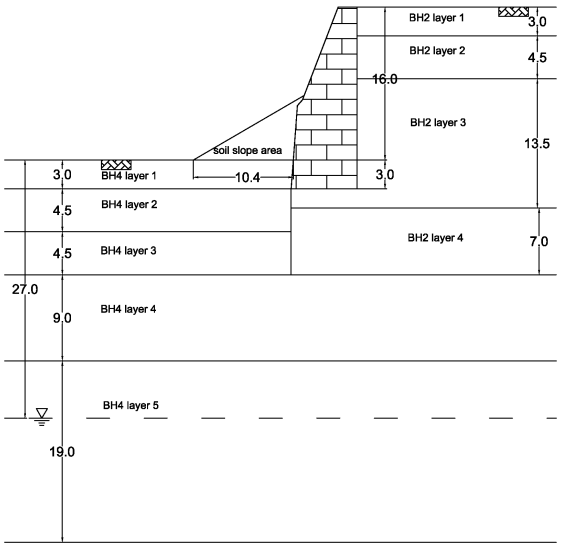


Figure 6. Section details and the depth of wall embedment (*all dimensions are in meter*)

The geotechnical investigation report furnished by ASI includes the data from four different bore holes (BH) in and around the fort premises. SPT tests have been conducted. The grain size distribution data of the soil samples from various depths in all the bore holes indicate that the underlying soil strata is fairly uniform with low plastic silts (clay content < 7 %) with intermittent occurrence of non – plastic sandy silt layers.

Two dimensional plane strain numerical analyses of the curtain wall of the fort between the bastion walls was carried out using PLAXIS 2D. The retained soil and the underlying foundation strata were modeled as homogeneous isotropic elastoplastic materials characterized by Mohr–Coulomb failure criteria. The soil profile used in the numerical analysis is shown in Figure 6 and the properties of the soil layers and the model used in the analysis are listed in Table 1.

Table 1 Properties of the soil and the brick masonry wall

Soil layer	SPT N	Soil type	Material model	Drainage type	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	e_0	E (kPa)	ν	c (kPa)	φ °	R_{inter}	k (m/day)
BH 02 Layer 1	6	ML-CL	Mohr-Coulomb	Drained	16.97	19.12	0.76	3600	0.35	5	24	0.67	8.64E-03
BH 02 Layer 2	23	SM	Mohr-Coulomb	Drained	16.97	19.12	0.76	8700	0.35	5	30	0.67	0.864
BH 02 Layer 3	37	ML-CL	Mohr-Coulomb	Drained	17.36	19.33	0.72	12900	0.35	5	24	0.67	8.64E-03
BH 02 Layer 4	42	ML-CL	Mohr-Coulomb	Drained	17.95	19.56	0.68	14400	0.35	5	24	0.67	8.64E-03
BH 04 Layer 1	13	SM	Mohr-Coulomb	Drained	16.77	19.12	0.76	5700	0.35	5	30	0.67	0.864
BH 04 Layer 2	16	ML-CL	Mohr-Coulomb	Drained	16.77	19.12	0.76	6600	0.35	5	24	0.67	8.64E-03
BH 04 Layer 3	24	ML-CL	Mohr-Coulomb	Drained	17.26	19.33	0.72	9000	0.35	5	24	0.67	8.64E-03
BH 04 Layer 4	40	SM	Mohr-Coulomb	Drained	17.75	19.33	0.67	13800	0.35	5	30	0.67	0.864
BH 04 Layer 5	43	ML-CL	Mohr-Coulomb	Drained	17.75	19.62	0.67	14700	0.35	5	24	0.67	8.64E-03
Soil slope area	13	SM	Mohr-Coulomb	Drained	16.77	19.12	0.76	5700	0.35	5	30	0.67	0.864
Masonry wall	-	-	Linear elastic	Non-porous	18.00	-	-	1.20E+06	0.2	-	-	-	-

The stability of the retaining wall is calculated by means of Phi-C reduction method. Initially, the factor of safety of the retaining wall with water table level (WTL) at 27 m below the existing ground level (EGL) was computed. The second phase of the analysis considers the water table at the top of the fill and the water seepage effect is accounted. The failure mechanisms of the two cases analyzed are shown in Figure 7 and Figure 8.

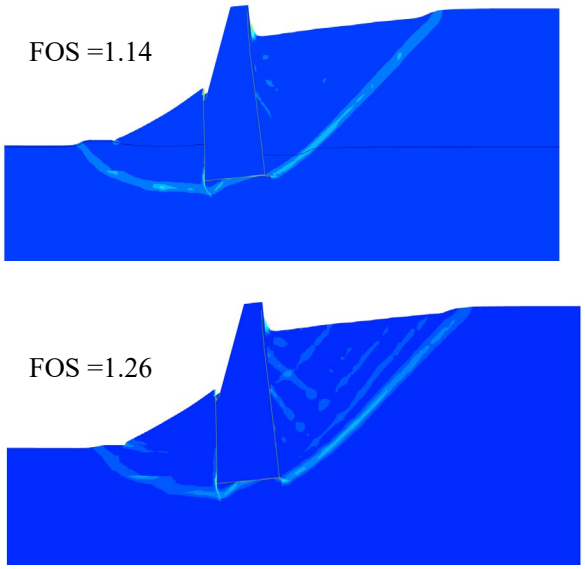


Figure 7. Failure mechanism for analysis carried out with and without ground water table in the vicinity

The factor of safety (FOS) of the curtain fort wall retention system, without the effect of water table in the fill area, is 1.26. However, the analysis which simulates the water table at the top level of the fill results in a much lower factor of safety of 1.14. Unacceptable build up of water pressure behind the retaining wall is capable of endangering the safety of the fort wall and hence, can result in the collapse of wall due to overturning or basal sliding. The collapse of the bastion wall and the curtain wall can be due to the build up of water pressure behind the retaining wall.

3 CONCLUSION

Based on the structural and geotechnical analysis, the following inferences can be ascertained.

1. The preliminary structural analysis concludes that the distresses shown on the structure especially at Gateway 2 and 3 are due soil settlement.
2. The gateway 3 has been adequately propped. Gateway 2 should be propped since it shows signs of distress similar to those seen in gateway 3.
3. From the geotechnical analysis, it can be inferred that it is critical to understand the sources that contribute to the flow of water through the fort. The preventive measures towards further failure seems to largely depend on controlling the percolation of water into the soil which is capable of inducing undesirable water pressures on the fill side, settlement of foundation soil and result in loss of structural integrity.

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