Numerical Modelling of Building Response to Underground Tunnelling - A Case Study of Chennai Metro

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Abstract- *The advancement in underground construction and use of Tunnel boring machine for construction is deeply studied. The construction of underground tunnel in soft ground involves potential risk of damage to super-structure and may lead to collapse of tunnel. Thus it is very important to predict the surface settlement before construction to minimise risk of collapse. Numerical modelling by FEM analysis of a building named Prema Palace in Chennai, India is studied and settlement of building is compared with in-situ settlement. This also includes the numerical modelling of building response to underground tunnelling by FEM analysis w.r.t. various parameters i.e., surface settlement (Ground and building), tilting*

Keywords — *Tunnel Boring Machine (TBM), Earth Pressure Balanced (EPB), Surface settlement prediction and monitoring instruments, Building settlement marker (BSM), Ground settlement marker (GSM).*

1. Introduction

A Mass Rapid Transit system (MRTS) is becoming popular in densely populated fast growing metropolitan cities. These are constructed in those cities which have high population density and congested area. Underground metro tunnel is best alternative to this situation. The construction of underground tunnels in urban areas involves the potential risk of ground movements caused due to tunnelling and it affects existing surface structures. Masonry structures are at particular risk of crack damage. The settlement is either due to low bearing capacity of soil or due to formation of cavities. These causes must be deeply studied before tunnelling so to prevent loss of life and property. Study of construction of a segment in Chennai metro and effect of settlement in influence zone has been studied and a FEM based numerical modelling for prediction of settlement has been suggested.

2. Objective and Scope of Present Study

The present study covers the following significant objectives with reference to process of construction of tunnels for Chennai metro.

a. Case study of construction of underground tunnel for a segment of Chennai Metro Rail and instrumentation and measurement of significant settlement in influence zone of tunnelling.

b. Physical measurement and Fem based Numerical modelling of settlement of Prema Palace- A Heritage building located in a segment of Chennai Metro.

c. Comparative study of in-situ settlement measurements and predicted settlement through FEM based Numerical modelling.

3. CASE STUDY OF CONSTRUCTION PROCEDURE OF UNDER-GROUND METRO TUNNEL

This is detailing of project from starting point to the end of tunnelling process. The data given below is the actual report of construction of Chennai metro.

A. Chennai City, Depth, Gradient and Design speed of Chennai Metro

Chennai is a metropolis city with present population of about 5 million est. 2011 with a population of more than 8 million. Presently Chennai Metro is under construction whose gradient is taken form 0.1%- 2% between stations and should not exceed 4% in ramp. The maximum speed designed is 80 km/hr. The depth of tunnel is 12 meter from ground level.

B. Description of alignment and estimated cost

Corridor 1:- It starts from Washermanpet and ends at Chennai Airport. Total length is about 23.085km in which Underground section is 14.300km, Elevated section is 8.785km and Total number of station are 18. Capital costs workout at March 2007 is Rs. 5,997 Crores

*Corridor 2:-*It starts from Chennai Central to St. Thomas Mount. Total length is about 21.961km in which Underground section is of 8.664 km and Elevated section is of 13.297km and Total number of station are 18. Capital costs workout at March 2007 is Rs. 5,106 Crores

C. Construction procedure

These are the basic step for starting of a metro's in any city in shown in figure 1. The choice of type of metro, alignment is decided after detailed project report or DPR report and further construction is started by using suitable techniques.

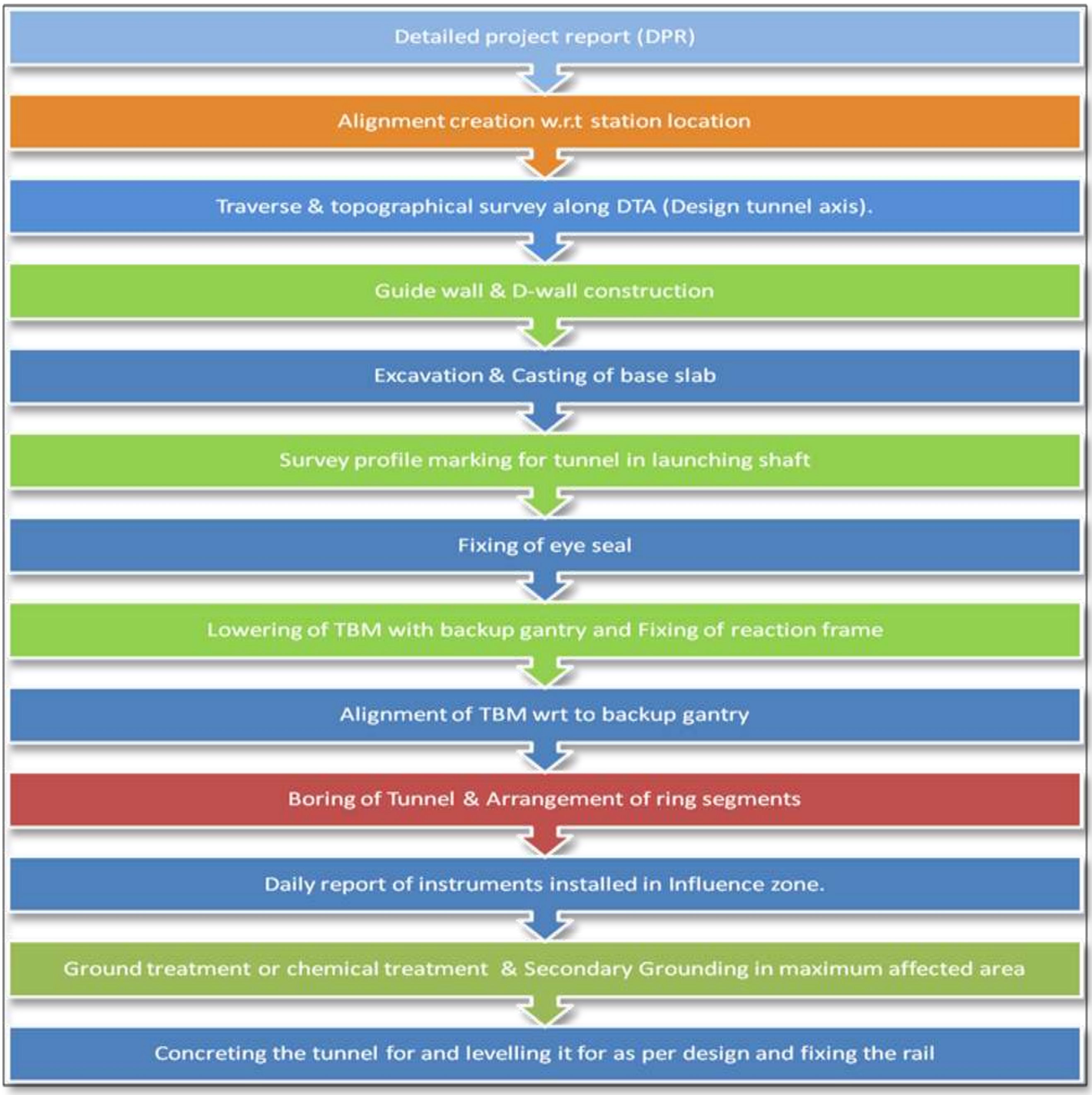

Figure 1: Construction Procedure

4. INSTRUMENTATION AND MONITORING IN INFLUENCE ZONE

Monitoring is carried out at planned locations selected along the alignment of the underground metro corridor tunnel. The purpose includes monitoring of the structures under construction together with the ground, buildings and other facilities within the predicted zone of influence. The monitoring will be performed to find settlement, groundwater level, and stress. Instrument which are used for monitoring purpose are Temporary Bench mark, Piezometer, Inclinometer and Tilt meter, Extensometer and Crack meter which are used to monitor vertical movement, water pressure, lateral movement of building, vertical deformation or heave with depth and crack width.

A. Monitoring level

There are 3 stages of monitoring level which are Alert, Action and Alarm level which is defined as when the settlement reaches 50%, 80% and 95% of expected level

B. Influence zone of twin tunnel

Influence zone is the area which is affected due to tunnelling. It is divided into 3 zones which are red, orange and green based on distance form centre of alignment as shown in figure 2.

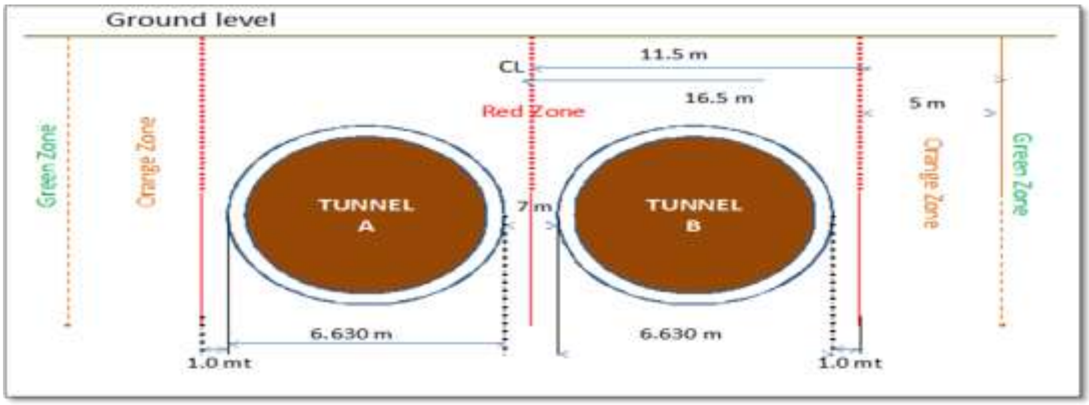

Figure 2: Influence Zone of twin Tunnel

5. REPORT OF MONITORING INSTRUMENT BETWEEN MAYDAY PARK AND CHENNAI CENTRAL

Data below shows the information between Mayday park to Chennai central of all the instruments which are used for monitoring purpose. Table no 1 shows the instrument name along with the monitoring levels.

A. Building Settlement Measurement

Data of building under monitoring and nearby installed Building Settlement Marker (BSM) is described below.

Table 1 show Point ID and location of building and settlement of Building Settlement Marker whose settlement with time is shown in figure 3,4,5,6 and 7.

The building under observation is Prema palace which is a heritage building located between Mayday park and Chennai central.

Settlement is noted by Auto level and reading is compared by previous reading at that point and also with base reading measured during Exciting building survey (EBS).

TABLE 1: BSM information near Prema palace

S.No	INST ID	POINT ID	Difference from previous reading(mm)	LOCATION
1	BSM 3031	3031	-16.069	CM-303 Prema Palace
2	BSM 3032	3032	-14.552	CM-303 Prema Palace
3	BSM 3033	3033	-15.879	CM-303 Prema Palace
4	BSM 3034	3034	-12.709	CM-303 Prema Palace
5	BSM 3035	3035	-12.709	CM-303 Prema Palace
6	BSM 3036	3036	-12.802	CM-303 Prema Palace
7	BSM 3037	3037	-11.83	CE-04 Travels
8	BSM 3038	3038	-12.4	CE-04 Travels
9	BSM 3039	3039	-12.449	CE-04 Travels
10	BSM 3040	3040	-12.553	CE-04 Travels
11	BSM 3041	3041	-12.413	Railway Wall
12	BSM 3042	3042	-12.551	Railway Wall
13	BSM 3043	3043	-13.5	Railway Wall
14	BSM 3044	3044	-13.6	Railway Wall
15	BSM 3045	3045	-12.8	Railway Wall
16	BSM 3046	3046	-13.2	Railway Wall
17	BSM 3052	3052	-13.7	CE-04 Travels

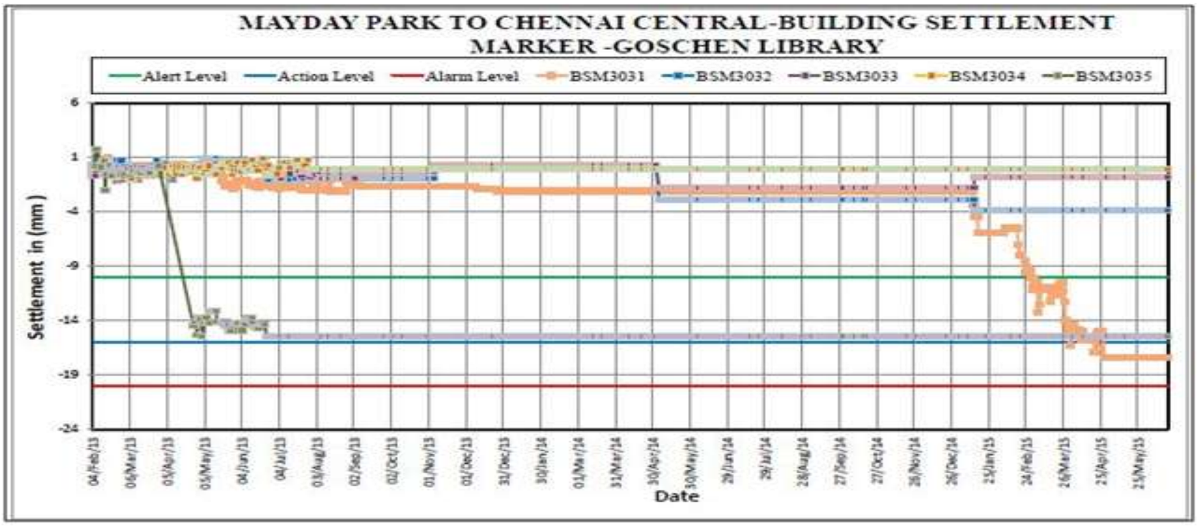

Figure 3: Settlement with time of BSM at Point ID 3031-3035

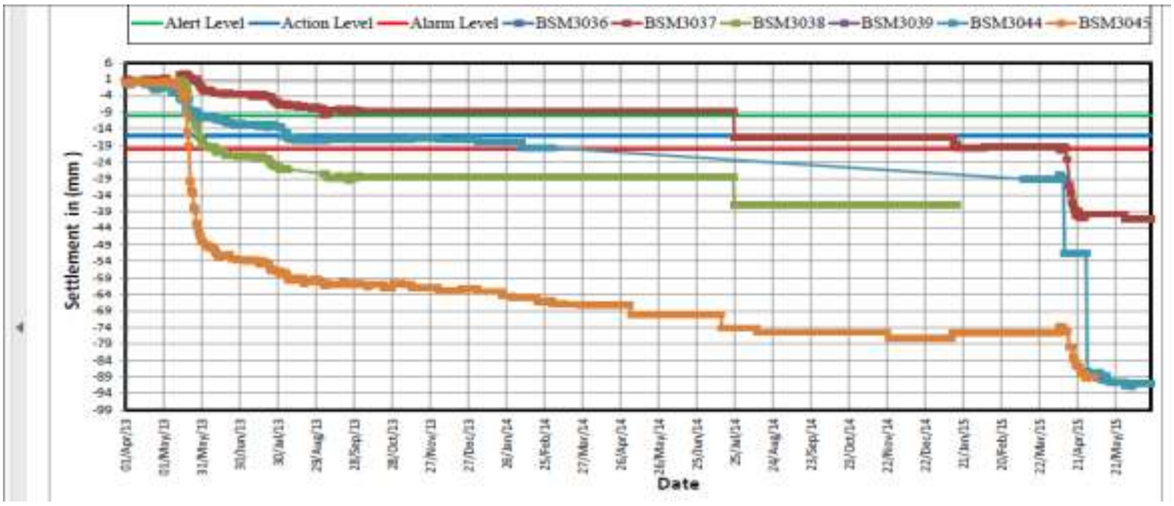

Figure 4: Settlement with time at Point ID 3036-3038, 3044 and 3045

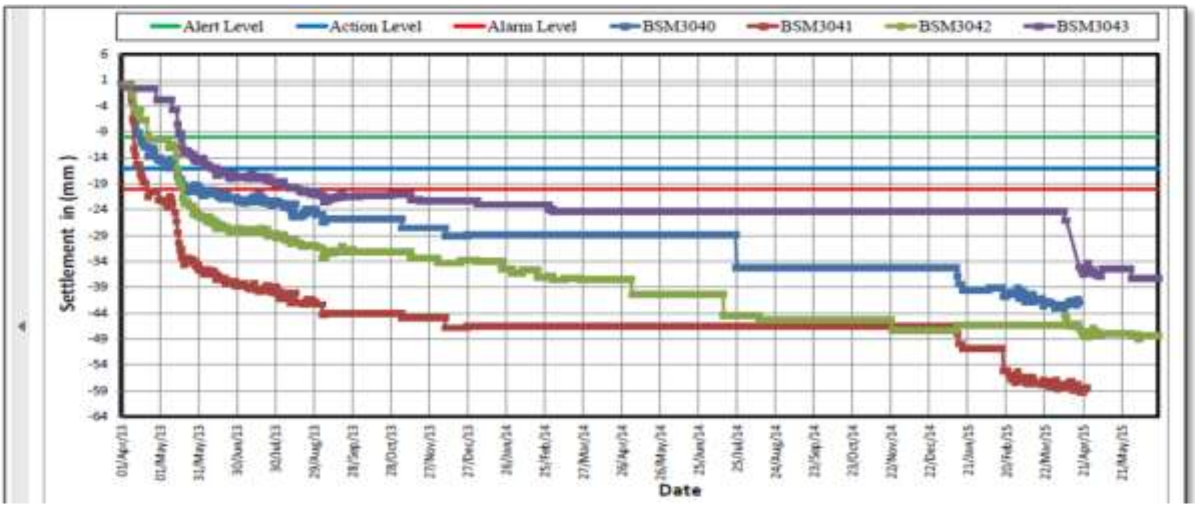

Figure 5: Settlement with time at Point ID 3040-3043

Figure 6: Settlement with time at Point ID 3036-3039, 3044 and 3045

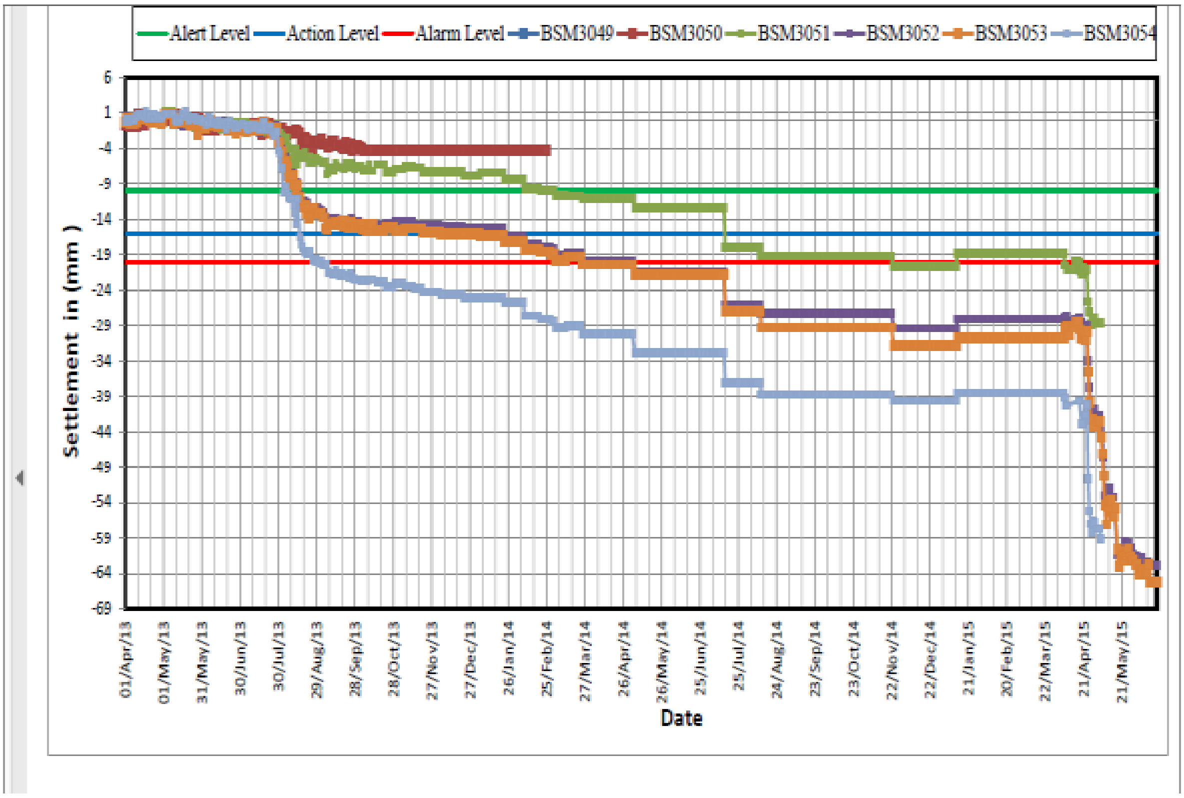

Figure 7: Settlement with time at point ID 3049-3054

B. Ground Settlement Marker

The list of various Ground Settlement Marker (GSM) with their location, point ID and their

Breached level is based on settlement of instrument which is near Prema Palace as shown in Table 3 and settlement of GSM is shown in figure 8,9,10 and 11.

Table 1: Summary of GSM

S.no.	Inst ID	Point ID	Location	Breach
1	GSP5101	5101	E1 Array	Breached Alarm Level
2	GSP5102	5102	E1 Array	Breached Alarm Level
3	GSP5103	5103	E1 Array	Breached Alarm Level
4	GSP5104	5104	E1 Array	Breached Alarm Level
5	GSP5105	5105	E1 Array	Breached Alarm Level
6	GSP5206	5106	E1 Array	Breached Alarm Level
7	GSP5107	5107	E1 Array	Breached Alarm Level
8	GSP5108	5108	E1 Array	Breached Alarm Level
9	GSP5109	5109	E1 Array	Breached Alarm Level
10	GSP5201	5201	E2 Array	Breached Alarm Level
11	GSP5202	5202	E2 Array	Breached Alarm Level
12	GSP5203	5203	E2 Array	Breached Alarm Level
13	GSP5204	5204	E2 Array	Breached Alarm Level
14	GSP5205	5205	E2 Array	Breached Alarm Level
15	GSP5206	5206	E2 Array	Breached Alarm Level
16	GSP5207	5207	E2 Array	Breached Alarm Level
17	GSP5208	5208	E2 Array	Breached Alarm Level
18	GSP5209	5209	E2 Array	Breached Alarm Level
19	GSP5302	5302	E3 Array	Breached Alarm Level
20	GSP5303	5302	E3 Array	Breached Alarm Level
21	GSP5304	5302	E3 Array	Breached Alarm Level
22	GSP5401	5401	E4 Array	Breached Alarm Level
23	GSP5402	5402	E4 Array	Breached Alarm Level
24	GSP5403	5403	E4 Array	Breached Alarm Level
25	GSP5404	5404	E4 Array	Breached Alarm Level
26	GSP5405	5405	E4 Array	Breached Alarm Level
27	GSP5406	5406	E4 Array	Breached Alarm Level
28	GSP5407	5407	E4 Array	Breached Alarm Level
29	GSP5408	5408	E4 Array	Breached Alarm Level
30	GSP5409	5409	E4 Array	Breached Alarm Level
31	GSP5410	5410	E4 Array	Breached Alarm Level
32	GSP5411	5411	E4 Array	Breached Alarm Level
33	GSP5412	5412	E4 Array	Breached Alarm Level
34	GSP5413	5413	E4 Array	Breached Alarm Level

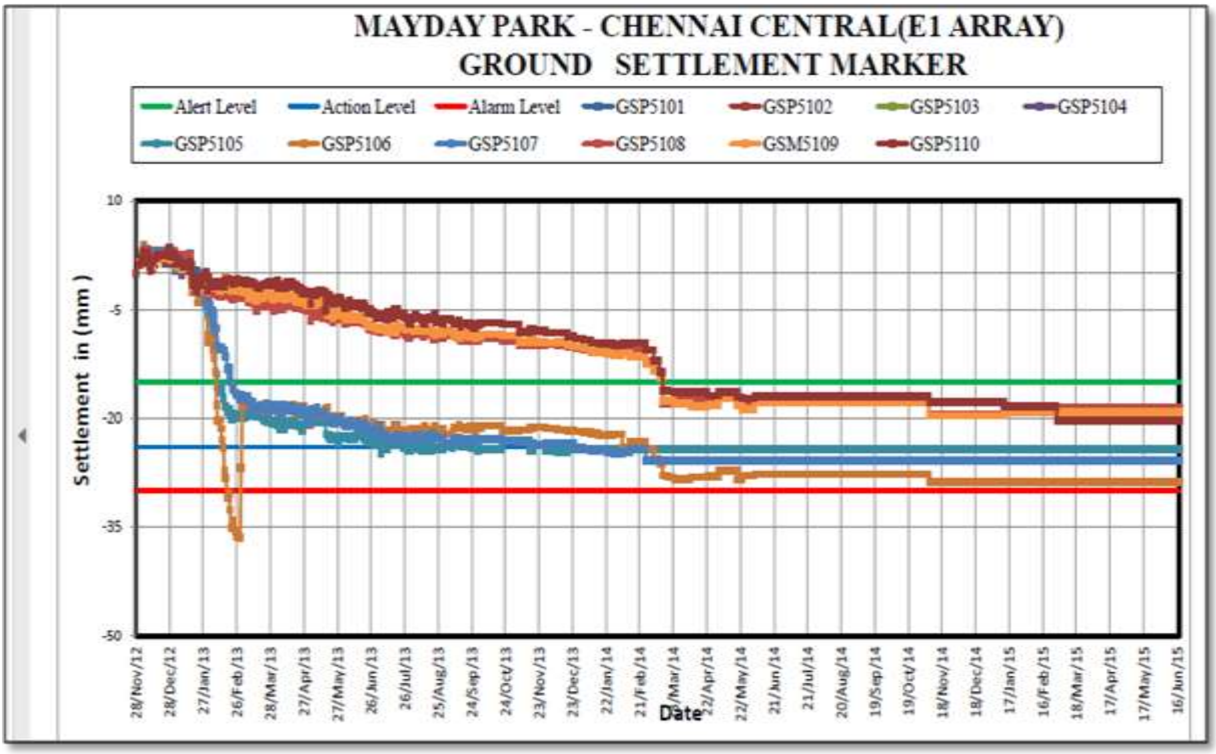

Figure 8: Settlement with time of GSM at point ID 5101-5110

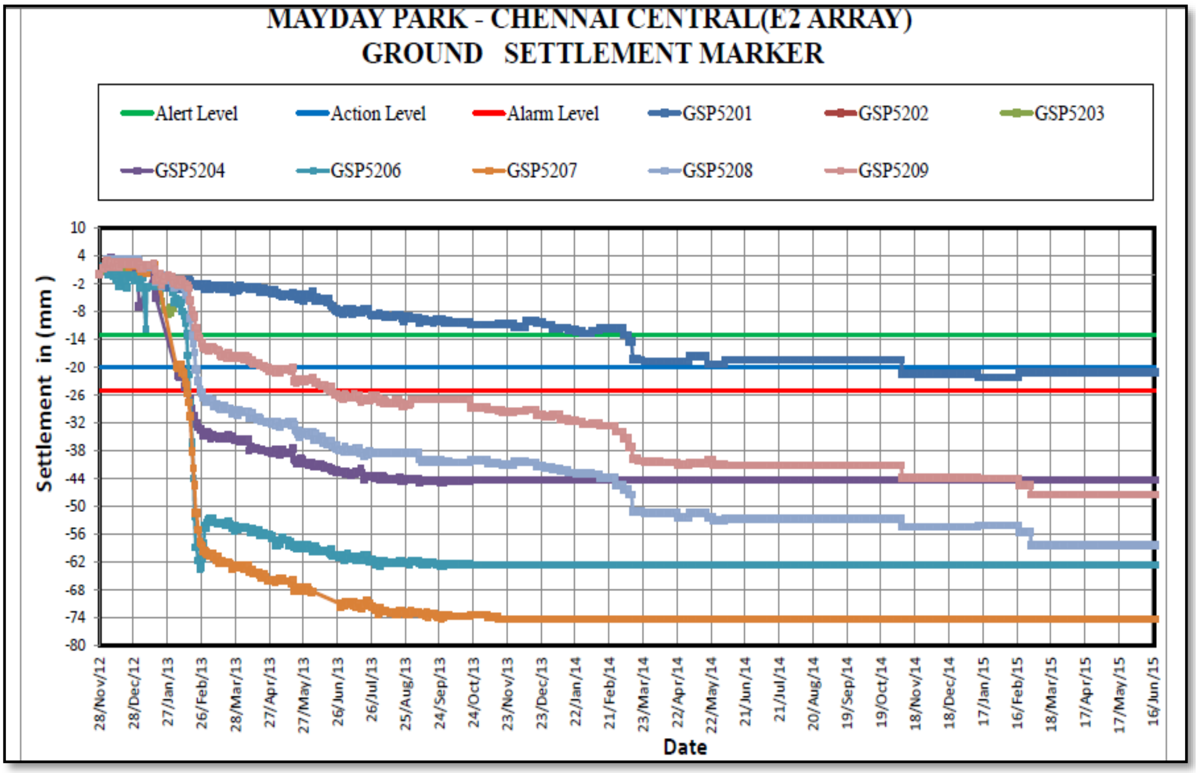

Figure 9: Settlement with time of GSM at point ID 5201-5209

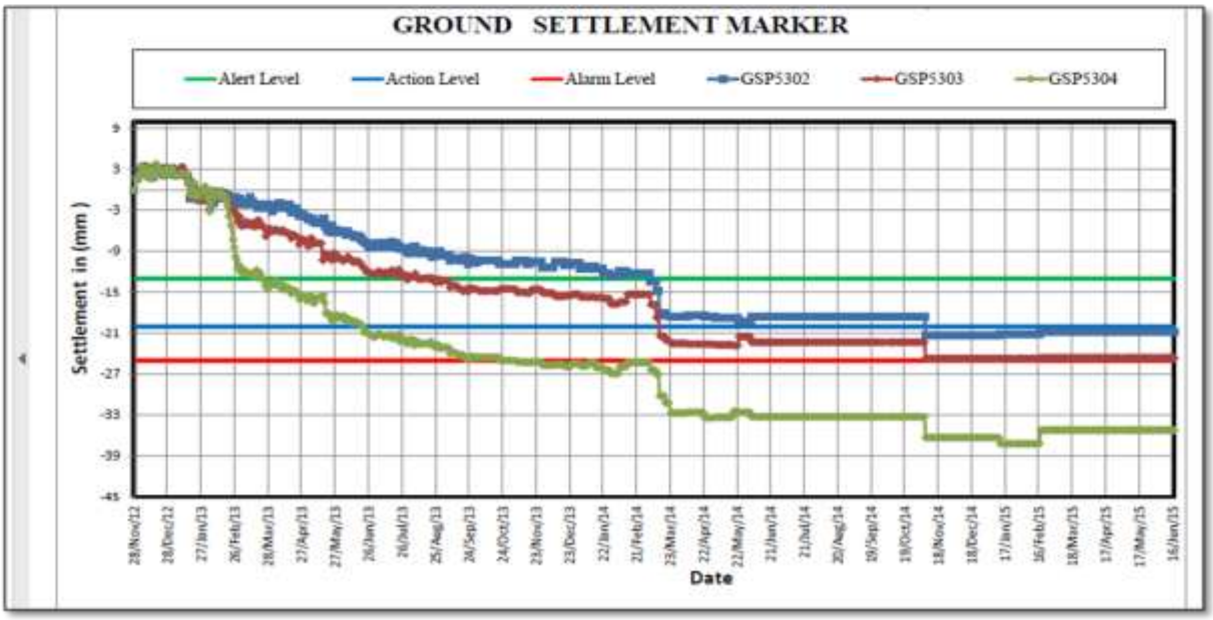

Figure 10: Settlement with time of GSM at point ID 5302-5304

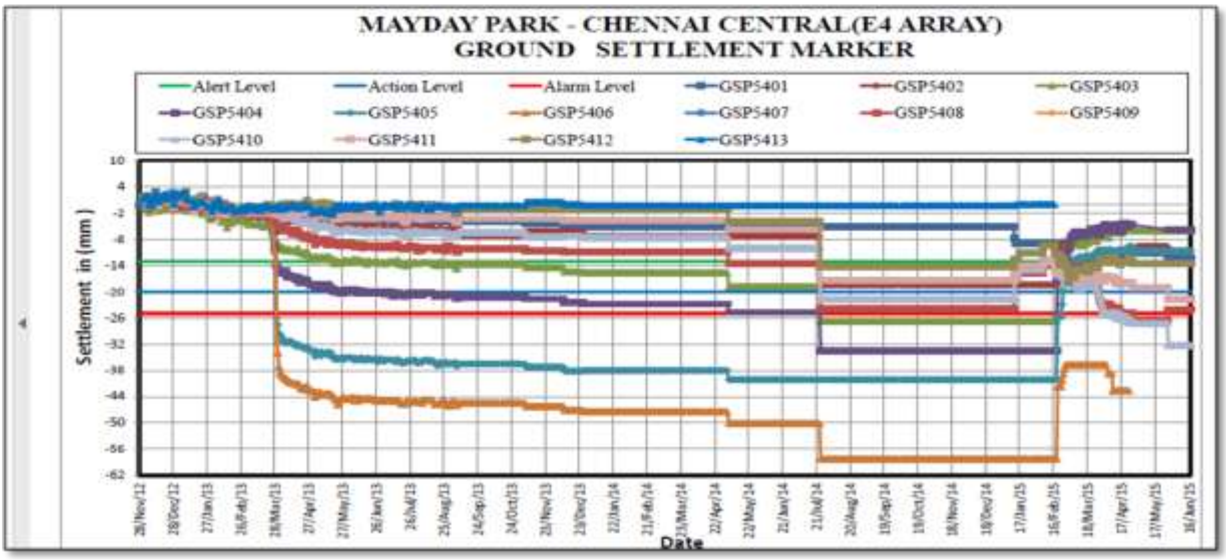

Figure 11: Settlement with time of GSM at point ID 5401-5113

6. INTRODUCTION OF NUMERICAL MODELLING BY FEM ANALYSIS

The increasing technology in computer software eventually leads us to the situation where structural engineers can apply 3D finite element calculations for ordinary design and calculation purposes. For settlement analysis due to tunnelling a finite element models is often known to over- predict the settlement and to under-predict the gradient of the settlement trough. The situation considered is a Metro Rail project and a Prema Palace- A heritage building which is present in influence zone of tunnelling in Chennai. The metro tunnels will be constructed near historical masonry buildings, founded on wooden piles, as well as newer buildings, founded on prefabricated concrete piles. Thus it is very important to predetermine the settlement which will be caused when TBM will pass through that point. Along the main part of the line the tunnels will run close to or beneath the toes of the wooden foundation piles. Both the piles and the masonry structure have little margin for deformation before damage to the construction will occur.

A. Finite element model for case study of Parema Palace- A Heritage Building in Chennai.

This is a realistic situation of Prema palace in Chennai which is built in influence zone of tunnel. It is 6.630 m diameter tunnel bored with its axis at a depth of 20 m below the ground surface (15.75 m soil above the tunnel lining). The situation of Prema palace is modelled using a 3D finite element model which is symmetric with respect to a vertical plane through the tunnel axis. The bottom of the mesh is at a depth of 30 m (5.75 m below the tunnel lining). In addition to the tunnel, a block of houses on piles is modelled adjacent to the tunnel at a distance of 10 m from the tunnel axis (5.75 m from the lining). The block of houses is 16 m long, 8 m wide and 12 m high above the ground level. The piles are found on the loose sand ground in which the tunnel is bored. Above this sand layer there is a 2 m thick clay layer, a 7 m thick peat layer and a 3 m thick fill as shown in figure 12.

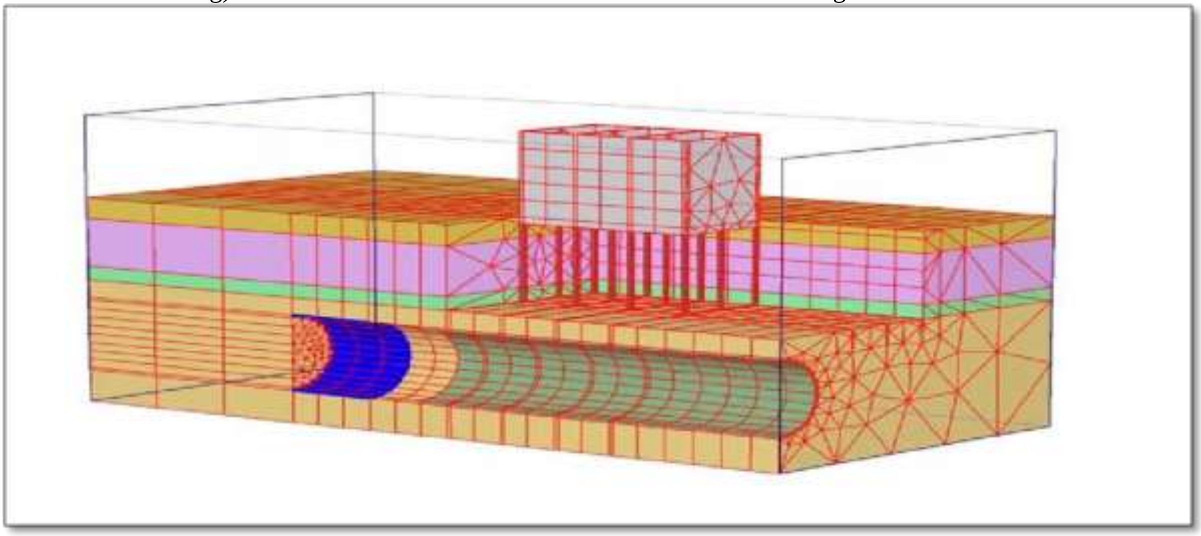

Figure 12: Model of Building and Tunnel by FEM

B. Results of Finite Element Analysis

The influence of tunnelling close to pile foundations on the bearing capacity of those foundations and the resulting deformations of the structure. Figure 13 shows the tilting of the houses due to the tunnelling process. At the left side the vertical settlement is 19.8 mm and at the right side the vertical settlement is 5.7 mm, which gives a gradient of 0.0012, i.e. less than 1:800. The gradient is slightly more than the gradient of the ground surface at the back-side of the model. This is due to the fact that the soil deformation and gradient at the pile tip level are higher than at the ground level.

A gradient by itself is not be harmful for historical buildings, but what might be more harmful is the torsion that occurs when the tunnel boring process passes the block of houses. The effect of torsion reaches its maximum value when the TBM has advanced about half way the houses

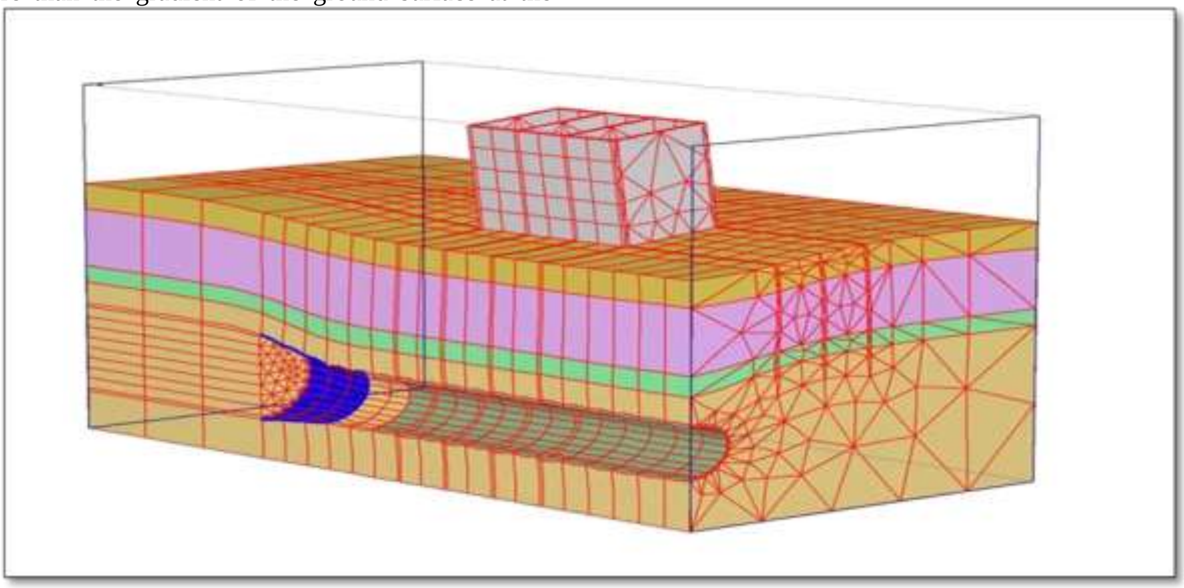

Figure 13: Total displacements at the end of Phase 20 and vertically tilting of building

Figure 14 it can be seen that the wall at the back-side has settled and due to the torsion effect cracks may be formed in the masonry walls, although the amount of torsion in this case is quite limited.

It is known that the width of the settlement trough above a tunnel is generally overestimated in a finite element analysis, and, as a result, the gradient of the trough is underestimated

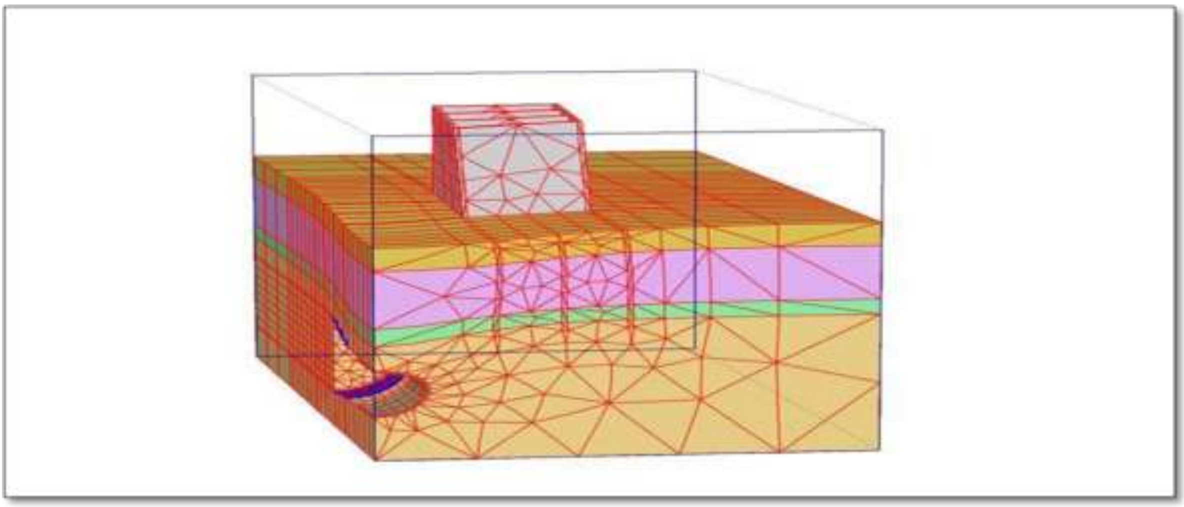

Figure 14: Displacements of building

Figure 15 shows the results after analysis, where the model has been cut at the back-side wall of the houses. Also the settlements of the ground surface are less in the stiff model than in the soft model. Especially in the stiff model the inclination of the ground surface near the houses is less than at the back-side of the model.

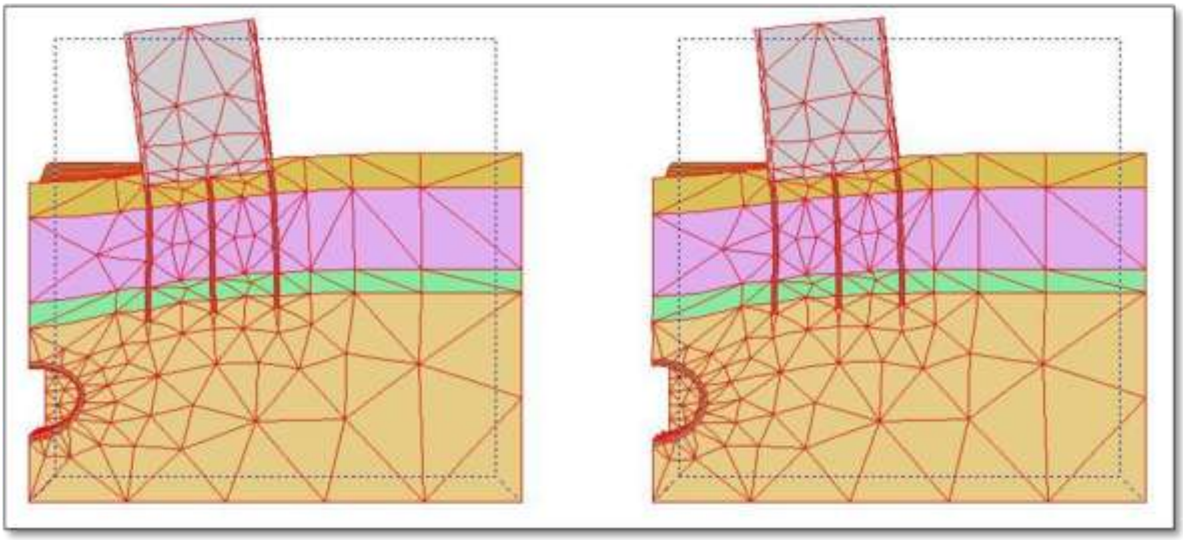

Figure 15: Total displacements at the back-side wall of Building

7. COMPARISION OF RESULTS

Results by FEM analysis and insitu monitoring settlement of Prema Palace is given in Table 4

Table 2

S No.	Point ID	Insitu Monitoring Settlement Result(mm)	Max settlement Results by FEM Analysis (mm)
1	BSM 3331	-16.069	-19.8
2	BSM 3332	-14.552	-19.8
3	BSM 3333	-15.879	-19.8
4	BSM 3334	-12.709	-19.8
5	BSM 3335	-12.709	-19.8
6	BSM 3336	-12.802	-19.8

8. CONCLUSIONS

The conclusion of this study is as follows

1. A case study of in-situ measurement of various settlement parameters using different monitoring instrument which lies in the influence zone of tunnelling is studied.
2. Numerical modelling of Prema palace in Chennai, India in done by FEM analysis and a comparison is made with in-situ monitoring parameters of the same building. In-situ settlement is 17.6mm and by Numerical modelling of building maximum settlement comes out 19.8 mm which is comparable.
3. By Numerical modelling of this structure it may be concluded that settlement is over predicted.

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