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EVALUATION OF CONSTRUCTING UNDERGROUND SPACES EFFECT ON HISTORIC BUILDINGS
CASE STUDY: MASHHAD METRO, LINE 3

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ABSTRACT

Underground spaces in contemporary cities have many uses. One major use of such spaces is to construct metro tunnels. Utilizing such spaces has a number of advantages but there is the potential of damaging existing buildings because of changes incurred to the substrate. This is more pronounced for historic buildings in cities with ancient origins. Computer modeling can estimate much of this damage before starting construction. Since Mashhad metro line3 passes under the city's old texture, this research was conducted using Plaxis 3D Tunnel software to create 15-node elements with 40×80m dimensions. Maximum loading relates to Imam Reza street buildings which had the most critical subsidence potential.

KEYWORDS: Excavation, Metro, Tunnel, Mashhad, Historic Buildings

With the rapidly growing population in metropolitan areas, mass rapid transit systems built underground have emerged as an effective transportation tool for relieving the saturated ground traffic in different parts of the world. However, the vibration resulting from the trains moving underground, propagating through the soils to the ground, has sometimes reached the level which can hardly be tolerated by the neighboring residents. As such, the problem of train-induced vibrations has received increasing attention from both engineers and researchers. For example, a project named CONVURT (Clouteau 2005) was conducted by the European Union recently, aimed at controlling vibrations from underground rail traffic. Within the frame of this project, Chatterjee et al. (2003) and Degrande et al. (2006a) performed in-situ vibration measurements in Paris and London, respectively. Meanwhile, a periodic coupled finite element-boundary element formulation was proposed by Degrande et al. (2006b) for predicting free-field vibrations caused by metro trains moving through the tunnel. By considering the periodicity of the geometry in the longitudinal direction of the tunnel, the discretization of the elements is limited to a single-bounded cell. Previous researches conducted along these lines can be generally classified into four categories as the analytical approach, field measurement, empirical prediction models and numerical simulation. A lot of researches on the ground-borne vibrations due to trains moving in underground tunnels were conducted by field measurement (Pan and Xie 1990) and empirical prediction models (Kurzweil 1979, Melke 1988, Trochides 1991, Hood et al. 1996), due to the fact that field measurement is the most reliable means for predicting absolute vibration levels in real situations and that empirical prediction models provide easier and cheaper ways for estimating the emission of vibration for underground railways in planning. However, neither of these approaches is suitable for the parametric study of different situations. In contrast, analytical approaches can be employed to conduct a parametric study once the model is established. However, owing to existence of the tunnel structure and variations in soil layers, the classical elastic wave theory is not considered as an effective tool for treating the ground-borne vibrations associated with the underground railway traffic. Earlier related works performed by analytical approaches were usually conducted in the two-dimensional format, such as Balendra et al. (1991), Metrikine and Vrouwenvelder (2000), among others. Recently, Forrest and Hunt (2006a,b) proposed a three-dimensional analytical model for studying the train-induced ground vibration from a deep underground railway tunnel of circular cross-section. The tunnel is assumed to be an infinitely long, thin cylindrical shell, whereas the surrounding soil is modeled by means of the wave equations for an elastic continuum. Concerning the vibrations due to trains moving in underground tunnels embedded by multi layers of soil deposits, numerical methods, such as finite element method, that are capable of simulating the tunnel structure and variations in soil layers appears to be most favored by engineers. However, traditional finite elements suffer from the drawback that the geometric radiation effect of the half space cannot be properly modeled. Thus, other schemes have to be incorporated to simulate such an effect. The viscous boundaries were used by Balendra et al. (1989) along

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with the finite elements to investigate the vibration of a subway-soil-building system in Singapore. Thiede and Natke (1991) used a similar scheme to study the influence of thickness variation of subway walls. Later, Chua et al. (1995) used a 2D finite-element idealization with the assumption of plain strain to reanalyze the same subway- soil-building system. The other popular scheme for modeling boundaries is the boundary element method. Andersen and Jones (2006) used coupled finite element-boundary element method to investigate the quality of the results gained from a two-dimensional model of a railway tunnel through comparison with those gained from a three-dimensional model. Degrande et al. (2006b) used a 3D periodic coupled finite element-boundary element formulation to study the dynamic interaction between a tunnel and a layered soil due to a harmonic excitation on the tunnel invert. In addition, Gardien and Stuit (2003) presented a finite element based modular model for predicting the vibrations induced by underground railway traffic. Such a model consists of three sub-models: the static deflection model, the track model and the propagation model. A parametric study was also performed to identify several factors that may affect the accuracy of the proposed method. Another scheme for simulating the semi-infinite boundary is the infinite element method, which has been successfully applied to problems related to ground vibration induced by traveling trains on the ground surface (Yang et al. 1996, Yang and Hung 2001).

According to the research done by Andersen and Jones (2006) for 2D and 3D combined finite element and boundary element analyses for railway tunnel structures, although 3D models are required for absolute predictions, the two-dimensional model provides results that qualitatively agree with those of three-dimensional models at most frequencies.

Consequently, for the soil-tunnel interaction problems of which the qualitative behavior, rather than the quantitative behavior, is of primary concern, a 2D model is considered sufficient. For the above reasons, as well as for the sake of reducing computational time, the 2D finite/infinite element approach proposed by Yang et al. (1996) will be adopted to investigate the wave propagation behavior of a soil tunnel interaction system due to trains moving in underground tunnels in the present study. With this approach, the soil-tunnel system is divided into two regions, i.e., the near field and far field (Fig. 1).

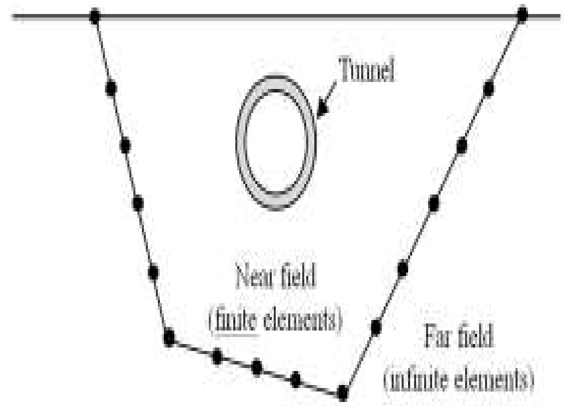

Figure 1: Schematic of the finite/infinite element approach

The near field, including the loads and other geometric/material properties, is simulated by finite (Q8) elements, and the far field covering the soils with infinite boundary by infinite elements. By such a combination, the inherent drawback of the finite element method in simulating the radiation damping for waves traveling to infinity can be overcome. Moreover, the infinite elements can be easily incorporated in existing finite element programs for structures, which, therefore, is likely to be favored by most practicing engineers.

Urban development is a global phenomenon whose highest rate of growth can be observed in developing countries (Houshyar & Alavi, 2013). This has caused much attention to underground spaces as in developed countries since these spaces have many advantages. For example, the temperate climate and stable temperature with slight variations make them a good choice for energy preservation and saving. The amount of such energy depends on underground space volume, depth, shape, relationship to surface spaces, and geological features (Liv & Zhong, 2011). The advantages of these spaces are not restricted to climate. Other factors like increasing productivity of land economical value, creating new uses, and doubling as shelter in times of disaster such as earthquake are important too. Moreover, underground spaces can be used as spacious reservoirs for buildings in urban infrastructure, excavated materials, water, and underground energies (Parriavn et al., 2007). Generally, it can be said that the underground space is hidden form the view and can hide many phenomena in turn (Bobylev, 2009).

Since metro routes must be ready to render services in critical situations and require extensive spaces to provide such services, and since accommodating them inside predetermined urban texture is immensely costly and difficult, the underground space seem to be the obvious choice. On the other hand, rail routes not only act as the main urban public transportation solution, but factors like energy savings, reduced noise and pollution, high transportation speed, and convenience for personal life, make them an inevitable remedy (Wei et al., 2012).

It is no secret that transportation is a major problem in today's cities and this has become more severe by increasing population. Mashhad requires rail transportation due to its 1.300,000 population and increasing number of immigrants. There is a shortage of broad and useful streets in Mashhad that intensifies the problem and adds to its heavy traffic. Therefore, constructing metro for a large city such as Mashhad is seriously considered (Qahreman, 2004).

The Mashhad urban rail transit project has been underway, however, the metro route under the old city texture poses risks to surrounding historic buildings. Therefore, the problem becomes more salient by investigating the impact of tunnel digging on these buildings.

RESEARCH BACKGROUND

There have been a number of studies on land subsidence caused by tunnel digging using various computer software. Some of these studies have been conducted by Clough et al. (1983) study of San Francisco water transfer tunnel, Hwong & Moh (1994) study of Taipei express train tunnel, Chiorboli & Morchesili (1996) study of Milan metro tunnel, Suwansawat (2002) study of Bangkok metro tunnel, and Crow (2003) study of Los Angeles water transfer tunnel. Also, 3D models have been used with finite element method and TSIM3D software which detects the impact of tunnel boring machine (TBM) parameters such as: cutterhead pressure, injection pressure, machine weight, and machine’s conic shaped shield on land subsidence (Kasper, 2006). Also, FLAC3D software has been used to analyze the sensitivity of various earth behavior models and the impact of cutterhead pressure and injection pressure on land subsidence for Madrid metro project (Lambrughi, 2012).

In a paper by Carter et. al (2004) Excavation and support of underground excavations beneath Canada’s Historic Library of Parliament Building, Ottawa was examined that This paper describes the concept assessment, the design development and support detailing, outlines the in This paper describes the concept assessment, the design development and support detailing, outlines the instrumentation installations developed at the design stage and implemented during construction and then presents some of the data from the excavation response behaviour of the rock mass and structure to the excavation works undertaken within and adjacent to the building. The Library of Parliament in the City of Ottawa in Canada dominates the Quebec side of Parliament Hill. Originally constructed in the 1860s and extensively rebuilt in 1953, the Library remains as one of three original buildings on the Hill. As existing space on Parliament Hill is at a premium and heritage and sensitive historic, visual and environmental requirements necessitated that all existing structures would remain visually unaltered, measures had to be taken to develop underground space in order to provide much needed upgrading of mechanical, electrical, heating and ventilation services to standards appropriate for preservation of the Library’s collections. Precedent had been set two years previously in construction of the Centre Block Underground Services Building by deep excavation into the rock mass beneath the perimeter and main chamber of the House of Commons that, with careful excavation and a comprehensive program of sequenced rock support installation, excavation could be undertaken in close proximity or even under the actual building structures. For the Library the key challenge was being able to develop sufficient underground space without compromising the stability of the fragile masonry building structure. Achieving this has required detailed design of complex excavation geometries and implementation of stringent control procedures to ensure that the required quality of excavations was achieved. Optimization studies lead to development of a concept involving excavation of an 8 m deep, 20 m diameter excavation, concentrically located directly beneath the core of the structure with associated cross tunnels, stairs, and an elevator, together with angled raise bores to facilitate the necessary services. Design of the excavations and of the monitoring arrays of instrumentation and detailed supervision of the excavation works has been key to ensuring minimal disturbance to the existing building by (i) requiring extremely high standards of perimeter excavation control and (ii) pre-supporting all load-bearing areas of the existing bedrock foundations adjacent to the excavations. Control of excavation sequencing and monitoring of movement behaviour of both the rock and the foundation zones of the structure have allowed control to be maintained of building and rockmass performance. This has been achieved by comparing as-observed movement trends with inferences derived from evaluation of the comprehensive output generated from detailed 2D and 3D numerical modelling undertaken during the detailed design stage.

The prediction of ground movements due to tunneling

A more detailed understanding of the mechanisms by which ground movements occur at tunnel excavations could be beneficial in predicting the volume loss, deducing the mechanisms of interaction with surface structures, and designing countermeasures against settlement. Empirical methods based on case history data, analytical methods (upper and lower bound and closed-form), laboratory 1g model testing, centrifuge modelling and numerical analysis have all been employed. For the potential value of numerical analysis to be realised, a sufficiently accurate constitutive model for the soil in the appropriate stress/strain range is required. Any modelling technique, either laboratory or numerical, must represent the tunnelling process to an acceptable degree of accuracy.

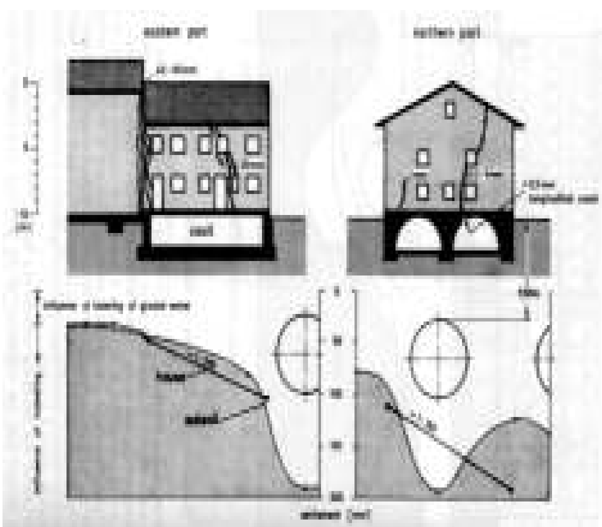

Figure 2: Interaction of a masonry building with vaulted basement to tunnelinduced settlements (Breth and Chambosse, 1975)

The masonry building interacted with the ground movements in a more complex way (Breth and Chambosse, 1975. Settlements were very large, up to 150mm maximum. One wing of the building was built on a very heavy vaulted basement, which appeared to contribute towards the wing behaving fairly stiffly. However, large cracks were still caused running vertically through the full depth of the building in the hogging regions of the settlement troughs. At one point a crack runs through the vaulted basement itself, possibly aided by the tensile horizontal ground strains that should in theory occur on the hogging side of the point of inflexion. Again some cracking occurred at abrupt changes in stiffness, causing fewer but larger cracks. Because the cover to diameter ratio was small and the settlements large, it is plausible that a failure mechanism through the soil was developing(Breth and Chambosse, 1975.

RESEARCH SCOPE

This study relates to city of Mashhad located at east of Iran.

According to studies, the Mashhad urban rail transit system should have 4 lines, and the first line will be constructed along southeast-northwest direction. The total length of this route is 57 km. Mashhad metro tunnels are planned as twins with 88.6m diameter that serve 2 separate incoming and outgoing lines. The area under study in this article is a segment with 1km length. The tunnel crown level is ~10m under ground level.

Line 3 is the case study of this paper which is 24 km and have 22 stages, that speed of trains in this line usually is 36km/h.

Fif.2-Mashhad city, Iran.

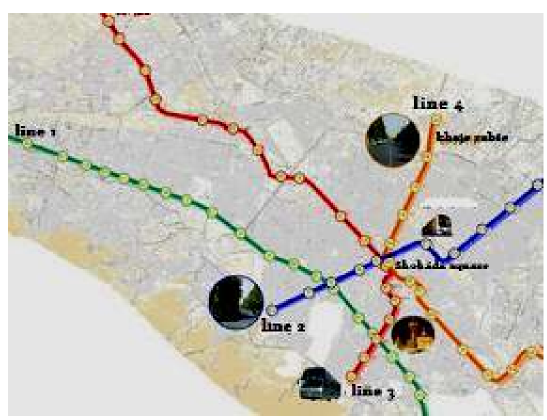

Figure 3: Map of approved Mashhad Urban Railway Lines

REGION'S GEOLOGY AND GEOTECHNICS

The region's soil is described as lean clay, and when mixed with sand (less than 10% sand) it is called lean clay with sand and sometimes silty clay or silty clay with sand. The ground water level in the area is -12m. The metro tunnel's floor and casing in the studied area go under ground water level (Khosrovi, 1997)(Soil Mechanics Engineering Services Consulting Engineers, 2002). based on area's geotechnical and geological features, there are 3 earth layers. The earth in numerical calculations was not drained and Mohr-Coulomb Model was used to describe its behavior. The geotechnical parameters required by this model are: expansion angle, elasticity modulus, Poisson ratio, friction, and expansion angle (γ, E, ν, c and φ)(Nemati, 2005) shown in table 1.

Table 1: Soil geotechnical parameters (table by author)

Soil properties	γunsat [Kn/M³]	γsat [Kn/M³]	E [Kn/M²]	ν	C [Kn/M²]	φ [°]	Soil depth [m]
Backfill	17	20	8000	30.0	20	25	4
Silty sand	17	20	30000	25.0	10	34	24
Lean clay	6.17	21	75000	25.0	30	22	12

RESEARCH METHODOLOGY

3D Tunnel Plaxis software was used to analyze. It is because the software inputs are simple which allow easy modeling of finite elements. Also, the output can be corrected easily. This program uses simple graphics so the user can conveniently create geotechnical model and meshing of finite elements based on vertical cross sections that represent the status quo (Behpor Gohari et al., 2006). To articulate the finite elements, modules with 80m width and 40m height were used. There were 15 elements in each node. This way, the underpass tunnel's nearby structures and constructed tunnels were modeled as shown in fig.4.

Bank Melli building which is near the tunnel was modeled by wide range and 200KN/m^2 loading. Haram with 60KN/m^2 weight was placed at the left side of the model. The model dimensions, structures, and distances between structures to tunnel axis in the finite elements model fully corresponded to their actual dimensions. It is noteworthy that the model's structure foundation was modeled to be flexible (Qahremani, 2004)(Gutierrez et al., 2003). Table 2 shows the modeled structures specifications.

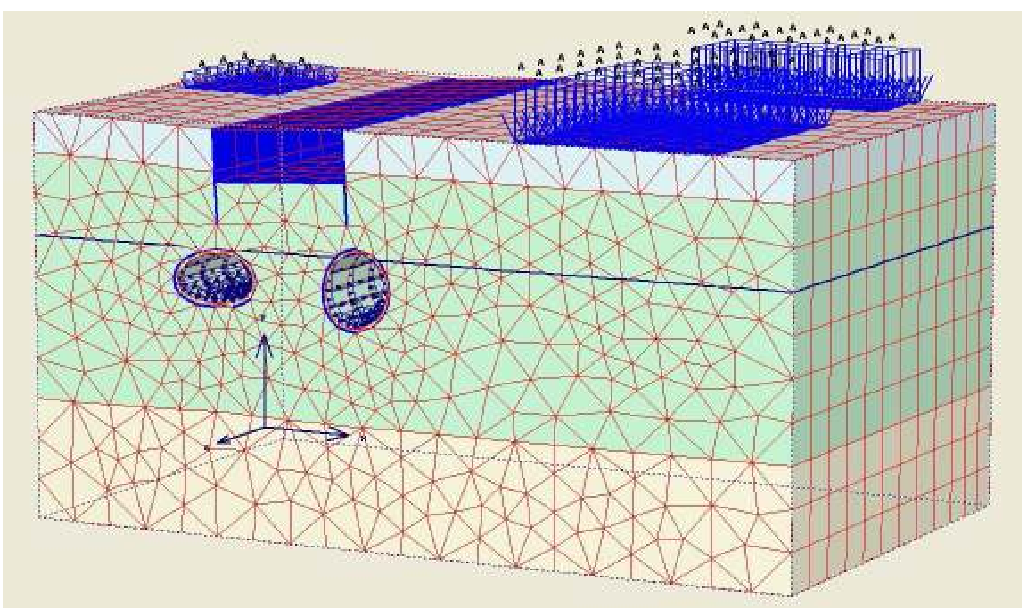

Figure 4: 3D finite element model

Table 2: Modeled structures specifications

Structure properties	EA [kM/m]	EI [kNm2/m]	W [kN/m/m]	A [m2]	D [m]
Abasgholikhan school	4×10^8	3.32×10^7	200	25×20	0.998
Haram	2×10^8	1.66×10^7	60	11×11	0.998
Underpass	1.2×10^8	1×10^7	10	14×1000	1.0
Lining	1.4×10^7	1.43×10^5	8.4	3.14×11.8	0.30

DISCUSSION & ANALYSIS

A TBM machine was used to excavate the route which was reasonable based on the excavated land type (fine grain without high shear strength). Most of the tunnel path is located under water table level and the soil is clay, silt, and running earth. Therefore, the work front line must be protected somehow. Based on earth type, machine diameter, and water table situation, and also according to economical and other restrictions, the best option is using earth pressure balance shield (EPBS) equipments which are mostly used in soft earth under water table all over the world . (Den hertog et al., 2005).

The subsidence was analyzed using Plaxis 3D Tunnel software across 5 scenarios which differed in distances of tunnel's centers from each other and the tunnel crown from ground level. Table 3 shows the tunnels' locations and structure subsidence (Khosrovi & Shafiee, 2008).

Table 3- Tunnels' locations and structure subsidence (author)

Center-to- center distance between tunnels (m)	Distance of tunnel crown level surrogate to ground level (m)	Abasgholikhan subsidence (mm)	Haram subsidence (mm)
15	6.11	2.2	2
10	6.11	2.1	1.1
20	6.13	2.3	6.2
15	6.15	4.2	2.2
10	6.15	8.1	7.1

The software calculations were processed in 3 stages: 1- Construction of adjacent structures and underpass, 2- Construction of first tunnel, and 3- Construction of second tunnel. The subsidence output in each step was used to calculate the next step (Qahremani, 2004). Table 4 shows the distance of structures to tunnel axis.

Table 4- distance of structures to tunnel axis

Structure title	Min. distance to tunnel axis	Max. distance to tunnel axis
abasgholikhan	**5.16**	**5.23**
Haram	**8**	**15**

The calculations imply that by increasing center-to-center distance between tunnels and proximity of tunnels to adjacent buildings, their impact on surrounding structures and model elements increases. However, the adjacent structures' earth pressure is important here (Bank Melli has an earth pressure of 200KN/m^2 and in this case, the most critical subsidence can be studied (Qahremani, 2004)(Moller et al., 2006).

By closing the distance between tunnels, their mutual impact increases, i.e. by closing stress bubbles, two tunnels influence each other and more subsidence results (Sadaqiani et al., 2006). Tunnels were also studied according to their crown level distance to ground level. It was thought that by increasing the depth, subsidence decreased. But analysis result showed the opposite case. The reason for more subsidence here was the uplifting phenomenon which appears in low depths. By increasing the depth and earth pressure on tunnel casing, the subsidence increases (Khosrovi & Shafiee, 2008)(Moller et al., 2006). Also, by comparing numerical computation results with precise instruments results, calculations were verified..

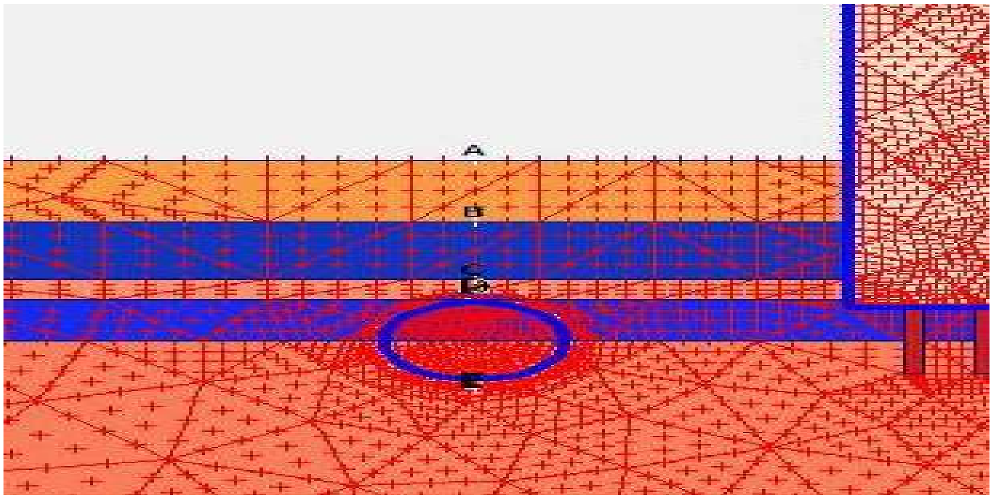

Figure 4: Stress measurement points

The data was processed during construction to obtain the overall tilt and settlement of the walls as the tunnel heading passed. The final wall settlements at the two locations are shown in Figures follow.

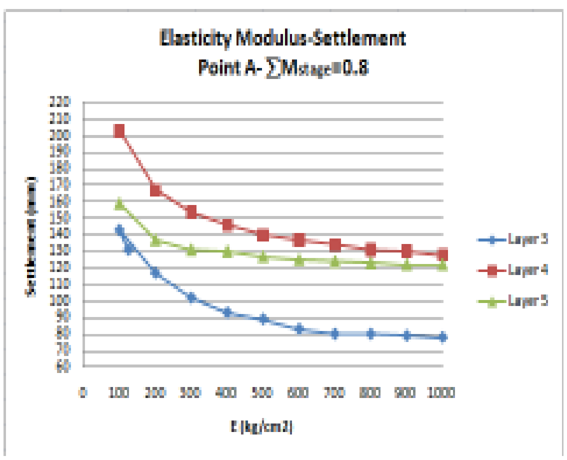

Figure 5: Changes in the subsidence of A point

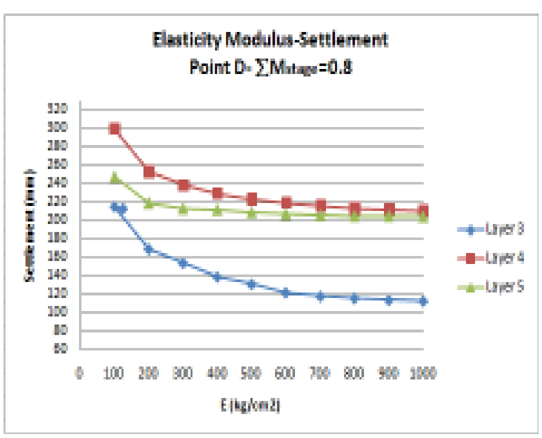

Figure 6: Changes in the subsidence of D point

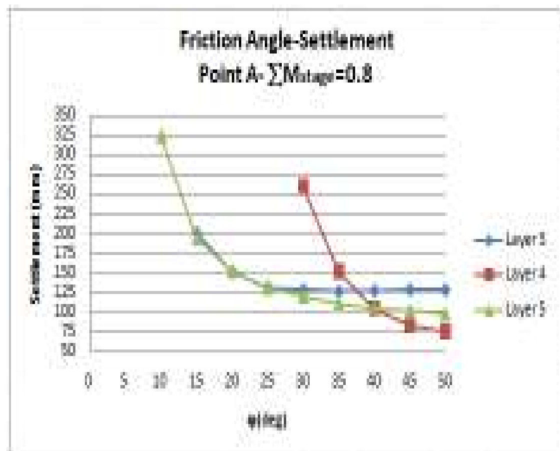

Figure 7: Subsidence changes with changes in coefficient of internal friction layer for A point

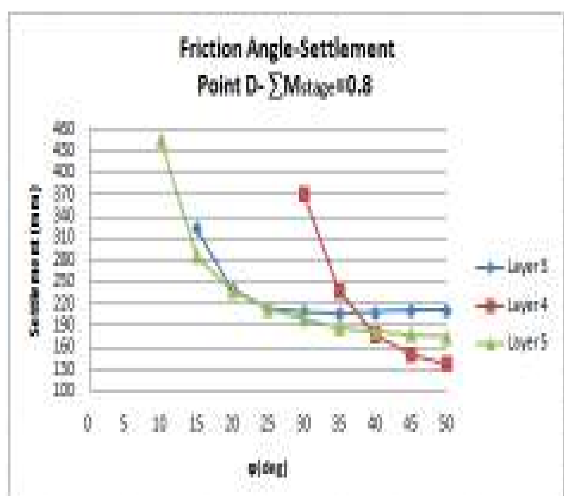

Figure 8: Subsidence changes with changes in coefficient of internal friction layer for D point

RESULTS

Based on the research objective which was the study of historic buildings along the metro tunnel path, it was observed that according to the structures' distance to tunnel axis, probably the highest impact from excavation will be borne by Haram. Also, there were some other observations:

1. It is expected that by increasing excavation depth, the subsidence should increase as well.
2. As was expected, by increasing the distance between tunnels' centers and their approximation to surrounding structures, the structures' subsidence increased.
3. The maximum amount of movement in the corresponding model is related to tunnels.
4. Structures' subsidence by increasing the distance between tunnels' centers and their approximation to surrounding structures- it is expected that the structures' subsidence increase.

And more results is so that:

In any numerical modelling procedure for prediction of tunnelling effects on structures, it is always important to adequately reproduce the 'greenfield' settlement trough without the building present. The importance of arching in the behaviour of larger historic buildings is confirmed. It can only occur when the settlement trough is spanned, as noted by Augarde (1997). The modeling indicates that this is likely to be the mechanism by which the east and west façades of the building escaped significant damage in the field.

The models generally over-predicted the damage by one category compared to that observed in the field, for example predicting "Slight" instead of "Very slight" damage. The distribution of damage also tended to be more localised in area than observed in the field.

It was demonstrated, in the modelling of more than one of the sites, that the presence of internal walls and large openings could have important effects on the response of the building as a whole. A three-dimensional analysis including incremental advance of the tunnel would be necessary to reproduce some types of damage observed in the field, particularly in internal walls in buildings.

Most of the models analysed on this project did not represent the building foundations by extra stiffness in the model. It isrecommended that foundation stiffness is only included if the foundations are of a reinforced concrete raft, or similar, and that any such modeling should be subject to further, careful verification.

Overall, the modelling procedures examined in this project have been shown to have excellent potential as a tool for stage three assessments of tunnelling effects on surface historic structures. There are no reasons in principle why the techniques could not be extended to tunnelling in other ground conditions, for example granular materials, other structural forms such as steel- and concrete-framed buildings, buildings with piled foundations and bridges.

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