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Performance Evaluation of Multi-Storey Building Subjected to Static and Dynamic Load Resting Above Tunnel In Stratified Soil.

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Abstract - *This study presents a comprehensive numerical investigation into the settlement behavior of multi-storey buildings with basements situated above unlined rectangular tunnels within stratified soil. The analysis encompasses configurations with 3 bay building directly positioned a top the tunnel as well as those with an offset varying from 5m to 20m at 5m intervals. Employing the finite element software PLAXIS-2D, both static and dynamic analyses are conducted, with the dynamic analysis incorporating the time history of the 2001 Bhuj earthquake. The results indicate that the settlement behavior of the buildings can be successfully analyzed using the finite element method. This study provides valuable insights into the settlement behavior of buildings above unlined tunnels and offers implications for design and analysis considerations in similar geotechnical contexts. The findings suggest that the presence of an unlined tunnel can significantly impact the settlement behavior of buildings.*

***Key Words*: Stratified Soil, Unlined tunnel, Time history analysis, Finite element analysis (FEM), PLAXIS-2D**

1. INTRODUCTION

In the Metropolitan cities due to lack of land for the infrastructure improvement/ development like the roadways, railways, sewer lines, communication cables etc., are going underground. If the buildings or any other structures built above these underground structure will have impact on the stability of the structures. Foundation plays a very impotent role in carrying the load from the super structure to substructure. The substructure is nothing but the underlying soil. The load received from the foundation is distributed to wide area below the foundation. The soil is an elastic medium which is good at taking the compression load. The below soil may fail due to two Criteria's either it may fails due to excessive settlement or bearing capacity failure. The existence of underlying voids has a negative impact on the ultimate bearing capacity and the settlement behaviour of shallow foundations.

In the present study, a multi-storey building resting above a rectangular unlined tunnel in a stratified soil was analyzed using a finite element-based numerical analysis geotechnical software, PLAXIS 2D, with the primary objectives of investigating the settlement behavior of a 3-bay building under static loading, analyzing its settlement behavior under dynamic loading using the 2001 Bhuj earthquake data. Assessing the settlement impact of the building's offset ranging from 0 to 20 meters from the tunnel centerline, and determining the acceleration at the top and bottom of the building resulting from the dynamic loads.

1.1 Finite Element Analysis

PLAXIS is a finite element package that has been developed specifically for the analysis of deformation, stability and flow in geotechnical engineering projects. The program is designed to simulate the behavior of soil, rock, and other geomaterials under various loading conditions, making it an indispensable tool for engineers and researchers working in the field of geotechnical engineering. At the core of PLAXIS 2D is its ability to model the complex, non-linear behavior of geomaterials. The software incorporates a comprehensive library of advanced soil and rock constitutive models, including the Mohr-Coulomb, Hardening Soil, and Soft Soil models, among others. These constitutive models enable users to accurately represent the stress-strain relationships, consolidation, and other fundamental properties of the materials being analyzed, ensuring the reliability and accuracy of the simulation results.

2. PROBLEM STATEMENT

The model comprises four layers of soil, extending from 0 meters to a depth of 100.1 meters. At a depth of 60.8 meters, there is a rectangular unlined tunnel measuring 13.65 meters in width and 12.27 meters in depth. The building's height ranges from 15 to 30 meters for 2-bay building configuration. The basement height varies, with floor-to-floor heights of 2 meters and 3 meters respectively. Each bay has a width of 5 meters as represented in the figure (1).

The soil comprises four distinct layers, each with specified properties as outlined in Table-1. For the building materials, plate elements are utilized for the basement and the remainder of the structure, with properties detailed in Table-2. Additionally, columns within the building are represented to separate bays node to node, with their properties specified in Table-3.

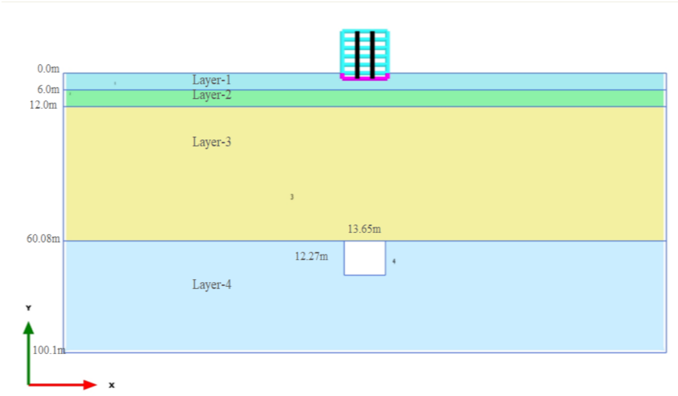

Fig-1: Soil profile

Table -1: Soil properties

Parameter	Unit	Layer1	Layer2	Layer3	Layer4
Soil model		Mohr-Coulomb			
γ_unsat	kN/ m^3	19	19	19	19
γ_sat	kN/ m^3	20	20	20	20
e		0.5	0.5	0.5	0.5
n		0.3333	0.3333	0.3333	0.3333
E	kN/ m^2	6.90E+05	1.30E+06	1.77E+06	1.77E+06
c'	kN/ m^2	400	400	400	400
φ' (phi)	°	17	17	17	17
ν (nu)		0.34	0.21	0.25	0.25
Soil class (Standard)		Medium fine	Coarse	Coarse	Medium fine

Table -2: Node to node anchor parameters used in the model.

Parameter	Unit	Column
Material type		Elastic
L Spacing	m	3
EA	kN	2.50E+06

Table -3: Plate parameters used in the model

Identification	Unit	Basement	Rest of Building
Material type		Elastic	Elastic
w	kN/m/m	20	10
Rayleigh α		0.232	0.232
Rayleigh β		8.00E-03	8.00E-03
EA	kN/m	1.20E+07	9.00E+06
E	kN/m^2	3.00E+07	3.00E+07
EI	kN m^2/m	1.60E+05	6.75E+04
ν (nu)		0	0

The 3 bay building is analyzed for various cases by varying the following parameters.

1. Height of the building: 15m to 30m [Basement(B)+ground floor (GF)+4 Floors to Basement(B)+ ground floor (GF)+9 Floors].
2. Offset from the tunnel centerline: 0m to 20m with 5m interval.

2.1 Numerical Modeling

Plaxis 2D version 23 is used for the simulation of the 3 bay building resting above the rectangular unlined tunnel. The building was analysed for both the static and dynamic condition. Numerical modelling is carried out taking the plane strain state of stresses. The 15-node triangular element with finer mesh density is used for the finite element discretization. The in-situ soil is simulated as Mohr-coulomb (MC) material for the static and dynamic analysis. For dynamic analysis, strong motion record of Bhuj earthquake respectively is used. The plate element is used for the basement and rest of the building. Nodes to node anchors are used to simulate the columns, which bifurcates the building into 3 bay. The analysis is carried out in the sequence indicated below.

1. Starting a new project.
2. Creating soil stratigraphy and tunnel using the geometry line feature and tunnel feature respectively, as shown below.
3. Defining standard earthquake boundaries.
4. Create the building using the plate feature, as shown below.
5. Creating and assigning of material data sets for soil for each layer (MC model).
6. Creating and assigning of material data sets for Plates.
7. Creating and assigning of material data sets for anchors. Prescribe the displacement using Bhuj earthquake data (occurred on January 26, 2001, in the Gujarat region of India, with a magnitude of 7.7 and peak acceleration is 9.8 m/s^2) Refer Figure(2).

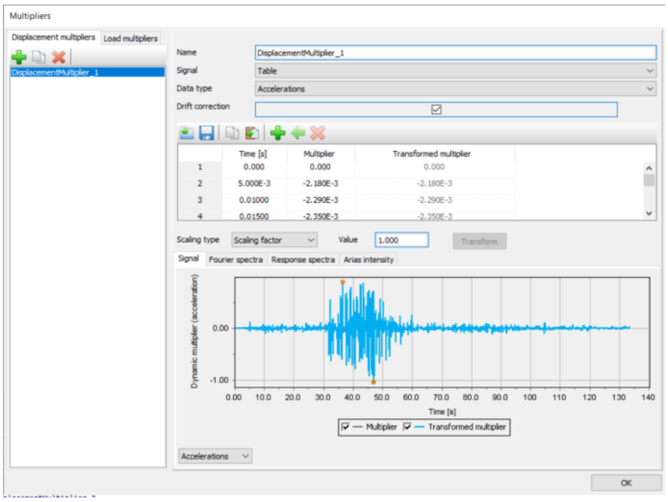

Fig-2: Strong motion record of Bhuj earthquake generated in Plaxis-2D.

8. Fine mesh generation for the model.

9. The calculation consists of four phases; the first phase is the initial phase consists of soil model. The second phase is tunnel phase, in this phase the tunnel is activated. Third phase is activation of building and the fourth phase is activation of dynamic component.

2.2 Output

Figure [3] shows the deformed mesh, the magnified image of how the soil body deforms after the analysis. Figure [4] shows the total displacement of the 3 bay building in static loading condition. Figure 5 shows the total displacement of the 3 bay building in dynamic loading condition. Figure 6 shows the Acceleration (ax) vs Dynamic time graph.

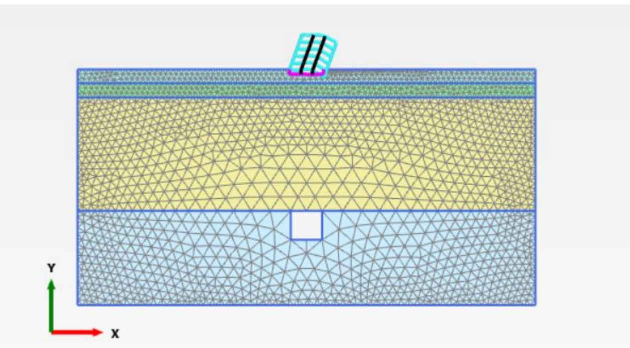

Fig-3: Deformed mesh of the model.

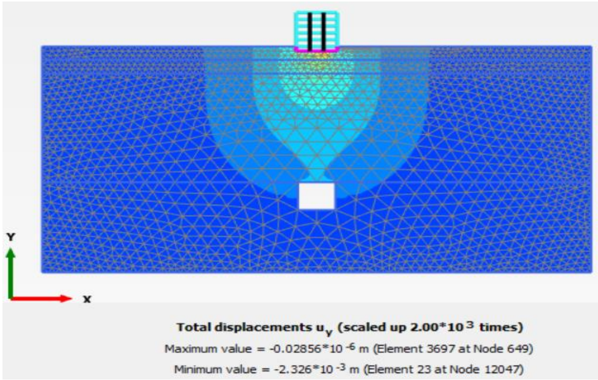

Fig-4: Total displacement in static loading.

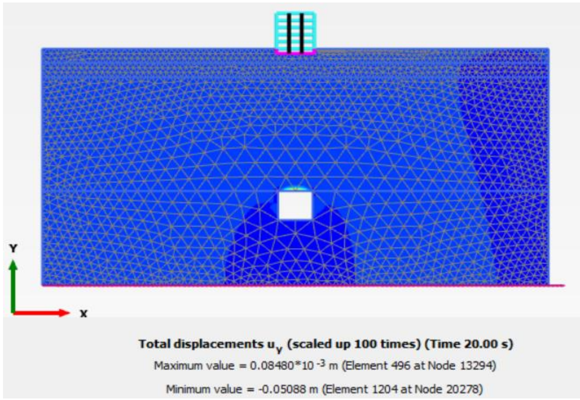

Fig-5: Total displacement in dynamic loading.

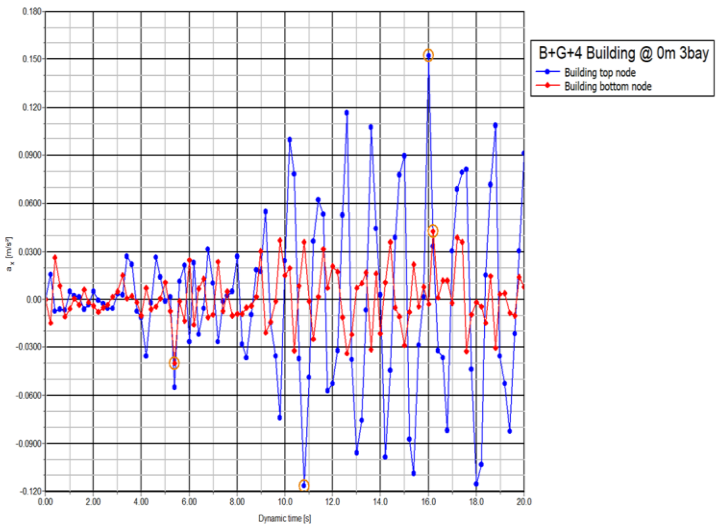

Fig-6: Acceleration (ax) vs Dynamic time graph.

2.3 Result and discussion

In the present study the multi-storey building resting above the rectangular unlined tunnel in a stratified soil is analyzed using numerical analysis with PLAXIS 2D, a geotechnical software based on finite element methods. The soil profile is accurately modeled, and properties are assigned to both the soil and other structural elements. Each bay of the building, whether in a 3-bay configuration, measures 5 meters. The basement has a depth of 2 meters, while the floor-to-floor height is 3 meters. Various scenarios are explored by altering the building's location. All cases are examined under both static and dynamic conditions. Under static conditions, the total vertical displacement of the building is measured. In dynamic conditions, time history is defined within the program, and forces resulting from dynamic acceleration are calculated.

The following are the results drawn from the numerical analysis.

Table 4: Settlement of 3-Bay Building directly resting above the tunnel.

3-Bay Building directly resting above the tunnel				
Levels	Settlement in Static Loading (mm)	Settlement in dynamic loading (mm)	Acceleration at the bottom of the building (m/sec²)	Acceleration at the top of the building (m/sec²)
B+G+4	2.326	50.88	0.043	0.153
B+G+5	2.920	49.01	0.042	0.091
B+G+6	3.737	22.60	0.040	0.084
B+G+7	4.448	25.52	0.078	0.164
B+G+8	5.841	23.39	0.043	0.097
B+G+9	5.540	23.69	0.04	0.088

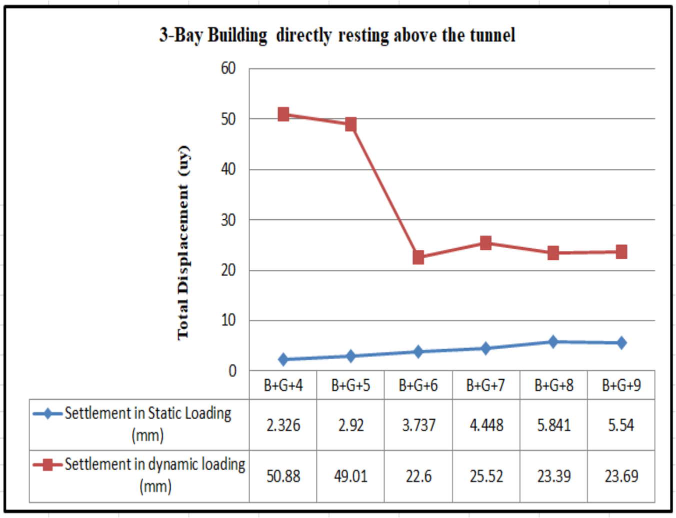

Chart-1: Building Height vs Maximum Horizontal displacement of 3-Bay Building directly resting above the tunnel.

From the analysis results, it is noted that the total vertical displacement under static loading conditions ranges from 2.326mm to 5.540mm for buildings with heights of 15m to 30m, respectively. These values fall well within the limits specified by IS 1904(1986). In dynamic loading conditions, the total vertical displacement varies from 50.88mm to 23.69mm for buildings with heights of 15m to 30m, respectively. The maximum acceleration at the top of the building is recorded for the configuration B+G+7, with a value of 0.164m/sec^2. Similarly, the maximum acceleration at the bottom of the building is observed for the configuration B+G+7, measuring 0.078m/sec^2.The analysis concludes that the total vertical displacement is higher under dynamic loading conditions compared to static loading conditions. Additionally, it is noted that the acceleration at the top of the building surpasses that at the bottom of the structure.

Table 5: Settlement of 3-Bay Building resting 5m from the tunnel centerline.

3-Bay Building resting 5m away from the tunnel centerline.				
Levels	Settlement in Static Loading (mm)	Settlement in dynamic loading (mm)	Acceleration at the bottom of the building (m/sec2)	Acceleration at the top of the building (m/sec2)
B+G+4	1.732	30.19	0.043	0.183
B+G+5	2.198	30.91	0.043	0.172
B+G+6	2.835	21.65	0.058	0.104
B+G+7	3.548	21.54	0.056	0.097
B+G+8	5.003	19.60	0.045	0.103
B+G+9	6.070	19.20	0.043	0.091

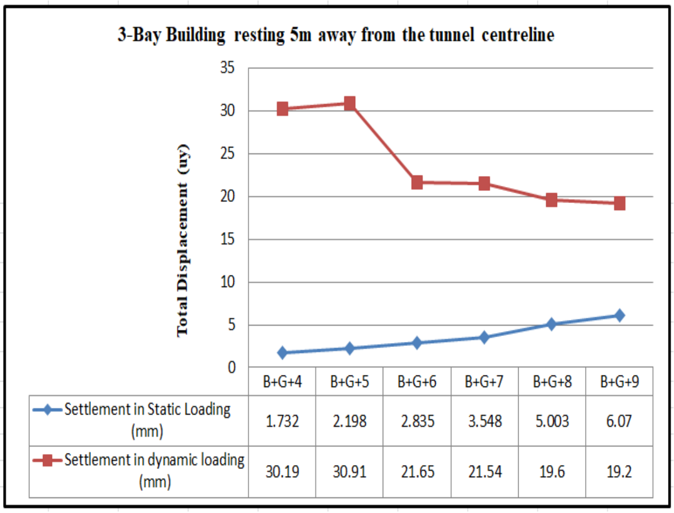

Chart-2: Building Height vs Maximum Horizontal displacement of 3-Bay Building resting 5m from the tunnel centerline.

Table 6: Settlement of 3-Bay Building resting 10m from the tunnel centerline.

3-Bay Building resting 10m away from the tunnel centerline.				
Levels	Settlement in Static Loading (mm)	Settlement in dynamic loading (mm)	Acceleration at the bottom of the building (m/sec2)	Acceleration at the top of the building (m/sec2)
B+G+4	1.674	30.23	0.099	0.188
B+G+5	2.286	31.13	0.050	0.174
B+G+6	3.294	21.48	0.047	0.104
B+G+7	4.154	21.48	0.053	0.097
B+G+8	5.021	19.49	0.053	0.104
B+G+9	6.019	19.28	0.049	0.093

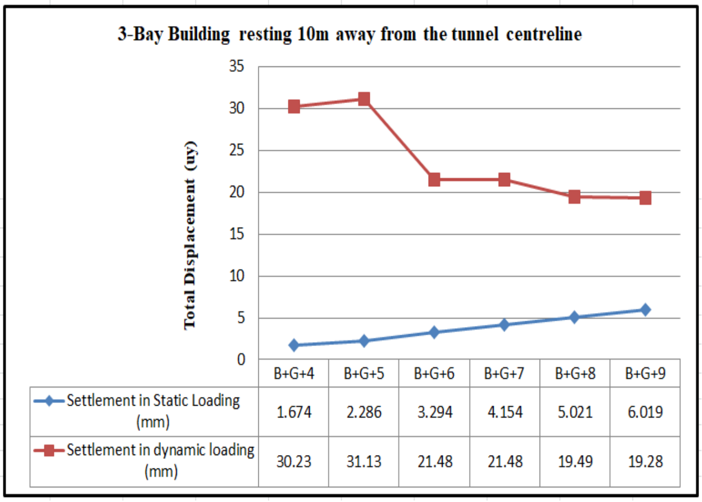

Chart-3: Building Height vs Maximum Horizontal displacement of 3-Bay Building resting 10m from the tunnel centerline.

Table 7: Settlement of 3-Bay Building resting 15m from the tunnel centerline.

3-Bay Building resting 15m away from the tunnel centerline.				
Levels	Settlement in Static Loading (mm)	Settlement in dynamic loading (mm)	Acceleration at the bottom of the building (m/sec2)	Acceleration at the top of the building (m/sec2)
B+G+4	1.737	30.15	0.091	0.189
B+G+5	2.487	30.86	0.054	0.172
B+G+6	3.394	21.29	0.066	0.105
B+G+7	4.298	21.25	0.065	0.097
B+G+8	5.077	19.46	0.052	0.104
B+G+9	6.291	19.00	0.051	0.092

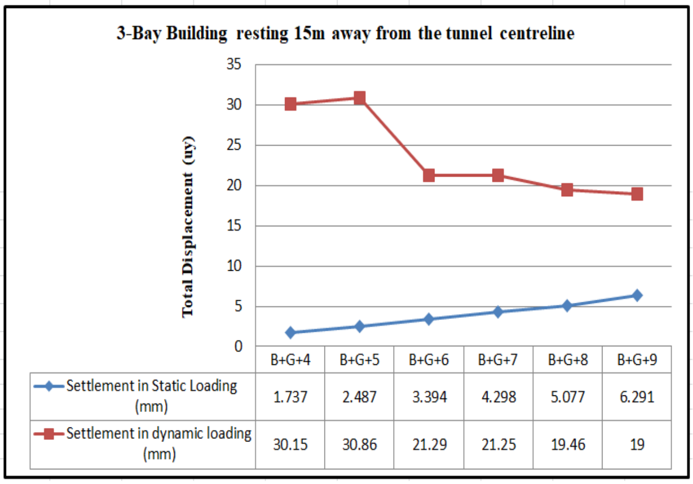

Chart-4: Building Height vs Maximum Horizontal displacement of 3-Bay Building resting 15m from the tunnel centerline.

Table 8: Settlement of 3-Bay Building resting 20m from the tunnel centerline.

3-Bay Building resting 20m away from the tunnel centerline.				
Levels	Settlement in Static Loading (mm)	Settlement in dynamic loading (mm)	Acceleration at the bottom of the building (m/sec2)	Acceleration at the top of the building (m/sec2)
B+G+4	2.022	30.03	0.054	0.189
B+G+5	2.679	30.69	0.066	0.173
B+G+6	3.488	18.52	0.056	0.107
B+G+7	4.392	18.56	0.053	0.099
B+G+8	5.374	19.29	0.055	0.104
B+G+9	5.702	19.21	0.056	0.091

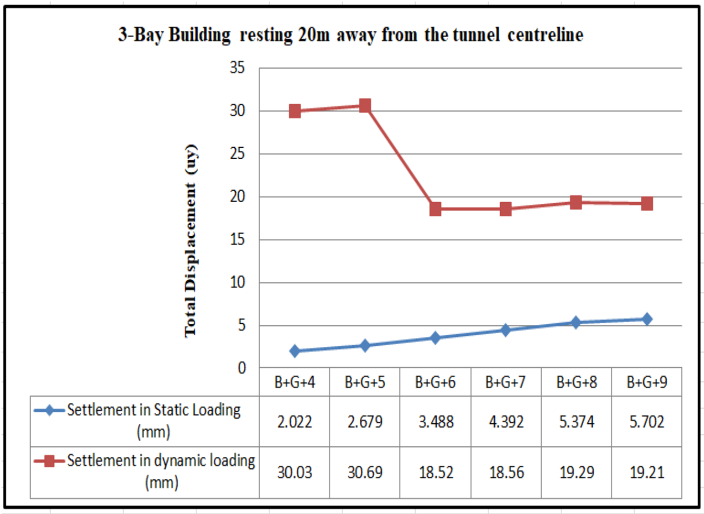

Chart-5: Building Height vs Maximum Horizontal displacement of 3-Bay Building resting 20m from the tunnel centerline.

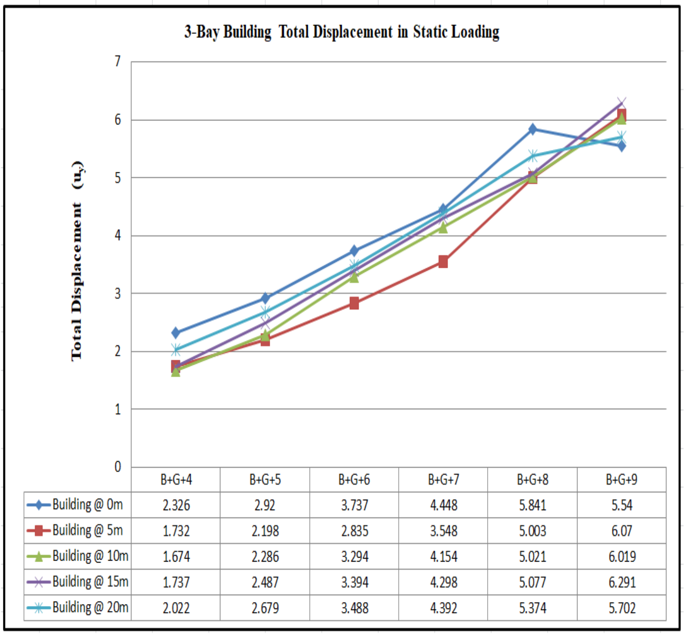

Chart-6: Building offset distance from tunnel centerline vs Maximum Horizontal displacement of 3-Bay Building in static loading.

The 3-Bay Building Total Displacement in Static Loading chart (6), several insights can be gleaned. The total displacement of the building is depicted across various configurations and building heights. The results illustrate a clear pattern of increasing total displacement with the building's height, indicating a direct relationship between the two factors. As the building height progresses from 1.674 to 6.291 for different configurations, the total displacement also escalates accordingly. Moreover, specific configurations, such as B+G+9, exhibit notably higher total displacements compared to others, emphasizing the influence of both building configuration and height on the overall displacement under static loading conditions.

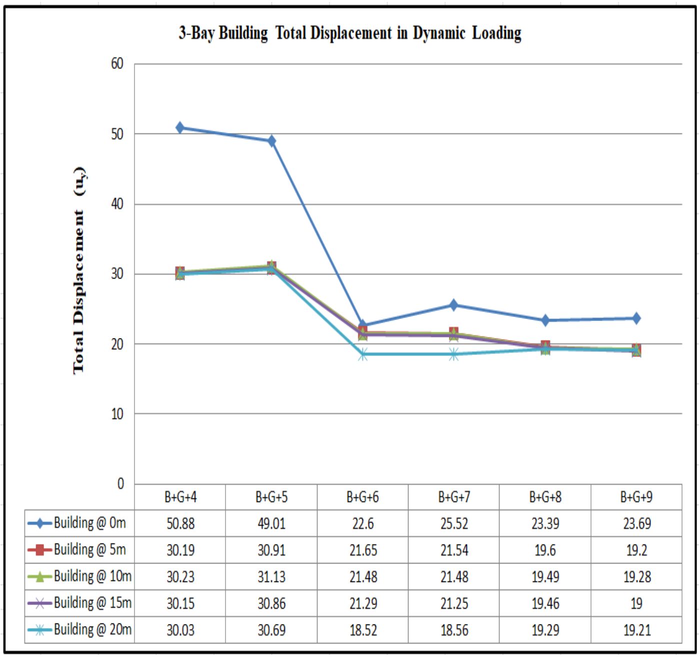

Chart-7: Building offset distance from tunnel centerline vs Maximum Horizontal displacement of 3-Bay Building in dynamic loading.

The 3-Bay Building Total Displacement in Dynamic Loading chart (7), several observations can be made. The total displacement of the building under dynamic loading conditions is depicted across different configurations and building heights. The results show varying levels of total displacement, with fluctuations observed for different building locations and configurations. Notably, the total displacement values differ from those under static loading conditions, indicating the impact of dynamic forces on the building's structural behavior. This suggests that the total displacement under dynamic loading conditions is influenced by factors such as building height and configuration, with certain configurations showing higher total displacements than others.

3. CONCLUSIONS

Based on the detailed parametric analysis of performance of multi-storey building resting above the rectangular unlined tunnel in stratified soil, the following conclusions can be drawn.

1. In static loading analysis of the 3bay building, as the height of the building increases from 15m to 30m, the settlement also increases significantly. This is because the weight of the building causes more settlement on the foundation as the height increases, leading to higher settlements.

2. In dynamic loading analysis, as the height of the building increases from 15m to 30m, the settlement is decreasing in both 3 bay building. This phenomenon can be attributed to the damping effects and dynamic response of the building structure, which may counteract the settlement increase observed in static analysis.

3. The investigation into the impact of building offset from the tunnel on settlement behaviour under both static and dynamic loading conditions reveals that the offset of the building does not exert a significant influence on settlement.

4. The difference in acceleration between the bottom and top of the building can be explained by various factors such as structural stiffness, foundation and soil conditions, and dynamic loads. The lower acceleration at the bottom indicates that the foundation absorbs some of the dynamic forces before they reach the top of the building, resulting in a higher acceleration at the top.

5. Under dynamic loading conditions, it is observed that; there is a distinct and abrupt decrease in settlement observed in the case of 6-story buildings (comprising of a basement, ground floor, and 6 additional stories) across all cases studied.

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