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Stage-by-stage control effect field analysis of steel material servo enhanced support system on lateral displacement and bending moment during deep basement excavation

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ABSTRACT

This study enumerates the stage-by-stage usefulness of the addition of a servo system to the lateral steel support system to improve the lateral load resistance of steel support members on an actual deep excavation site. A field case is found in a project of Triumph Unit building block, where a 14.20 m basement is constructed near the existing high traffic highway and high-rise buildings. It is therefore important to choose an appropriate excavation pit lateral support system to ensure the safety during excavation. At the field site, the basement execution works are divided into 5 construction stages. The excavated pit wall displacement and bending moment caused by excavation process are controlled using the steel material servo combined load support at each respective construction stage. The results from field work authenticate the steel servo enhanced support system application on an actual basement construction site. With the application of steel servo enhanced axial loading capacities, the excavated pit induced lateral displacement and bending moment are effectively restrained within the project acceptable alert limits. Moreover, the obtained field results correlate well with previous and current numerical literature data. This study provides a unique chance to advance the steel material servo enhanced support system application to actual deep basement projects with acceptable displacement and bending moment control requirements.

1. Introduction

Requirement for deep basement project construction option in congested urban areas is necessary in recent years due to limited urban land space [1]. However, the uncontrolled excavation pit construction process induces soil displacement and bending moment challenge that may result in adverse impact on proximity structures [2]. This challenge is related to the inadequate control effect capacity of the current lateral support system such as steel bracing material support [3]. Wang [4] obtained the excavation-induced displacement and bending moment in the range of 40–125 mm and 200–1100 kN-m respectively when steel bracing material support was used on different deep excavation projects of depth ranging over 10 m. However, extra sized steel sections had to be used, which increased the cost and the bracing labour to meet the required displacement and bending moment limits imposed on the projects. Study

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reported by Nicotera et al. [5] adopted steel bracing material to support a deep foundation pit in soft rock, and managed to reduce the displacement and bending moment by 33% and 19.50% on average respectively as compared with using other support members such as concrete struts. Hwang [6] explained that with the adoption of preloaded steel bracing material as a deep basement excavation internal support structure, the excavation-induced displacement and bending moment are controlled to the extent of the predefined stiffness of the steel bracing material support. The predefined steel material stiffness cannot be increased in a loaded condition [6]. The steel bracing material loses axial force in unexpected circumstances where the lateral load exceeds the support stiffness [6]. Eventually, the occurring displacement and bending moment exceed allowable limits by the standards [6].

Steel bracing support stiffness enhanced by the hydraulic servo system has been reported by some researchers recently [7,8]. Specifically, Di et al. [7] investigated the deformation control mechanism of steel bracing material with servo support and steel bracing material without servo support based on simulated measured data. They divided the excavation pit into two parts. The first part was supported with steel bracing material alone while the second one was supported with a servo steel material enhanced system. They found that the steel bracing material alone in the excavation pit which was without servo, exhibited maximum of 86.7% axial force loss. In another study, PLAXIS 3D commercial finite element software was used by Ye et al. [9]. They analysed the basement excavation induced deformation with respect to the steel bracing material support system during the excavation process. Their measurements demonstrated that the steel bracing material support without servo exhibited more than 65% loss in axial loading capacity. Ming-Guang et al. [10] adopted the FLAC 3D, commercial software programme for a case study on the Taipei National Enterprise Centre (TNEC). The deep excavation was numerically modelled to assess the effectiveness of hydraulic servo steel-supported excavation-induced deformation control, and their results were consistent with the determinations of Di et al. [7] and Ye et al. [9].

Ming-Guang et al. [10] pointed out that the application of servo method in deep excavation is based on engineers' experience and depends wholly on the available commercial software programmes such as PLAXIS 3D and FLAC 3D. Servo technology is affected by slenderness ratio of steel struts, cross-section shape of steel struts, end conditions of steel struts, geometry of excavation, earth retaining wall type, construction procedure and servo axial load application process [11]. Controlled experimental works for analytical based solution to comprehensively consider these factors is a challenge [12]. Thus, simple and practical experimental based analytical solutions cannot fully predict the excavated pit wall induced displacement and bending moment for steel material enhanced servo method application [12]. Even though numerical simulation is capable of properly modelling the excavation complexity and the aforementioned factors, the servo steel material technology support modelling process requires extensive computations and the simulation procedure in itself is complicated in practice [13]. The precision of numerical simulation is significantly affected by the choice of parameters. The preferred parameters primarily depend on the test method, and are practically difficult to determine [9]. Comparatively, field construction site case provides a suitable approach and first-hand experience to explore the servo steel material supported system in controlling the excavation-induced displacement and bending moment of the excavation pit and surrounding environment [10]. Presently, there are few studies on the steel material servo technology application in deep excavation, and the limited available studies are based on numerical simulation [8,11]. With the process of urbanisation, there are more deep excavation projects adjacent to structures and a strict requirement for displacement and bending moment control. Thus, research regarding this phenomenon is still required. Therefore, this research takes an actual field project and seeks to advance and authenticate the actual field construction site application of steel material servo enhanced technology in restraining the displacement and bending moment caused by excavation.

In this study, a real construction filed case of a 14.20 m deep basement of a high-rise building "Triumph Unit building block project in Hangzhou city, China" is investigated by observing the actual support structure lateral displacement and bending moment with respect to the inclusion of the servo system to the lateral steel material support system. The construction site basement execution works are divided into 5 construction stages and each construction stage is exclusively investigated. The induced lateral displacement and bending moment during basement soil excavation process at each construction stage are controlled using the steel material servo enhanced support system axial loading capacities before proceeding to another construction stage. The results from the actual field work are correlated to the numerical literature data to validate the application of numerical simulation on analysing the capacity of steel material servo enhanced support system. Moreover, the nature of the building block basement excavated soil is primarily of soft silt with silty clayey properties. The building block project is adjacent to a high traffic highway, and high-rise buildings are within the enclave of the building project basement excavation. Hence the strict control requirement of the project basement construction relative

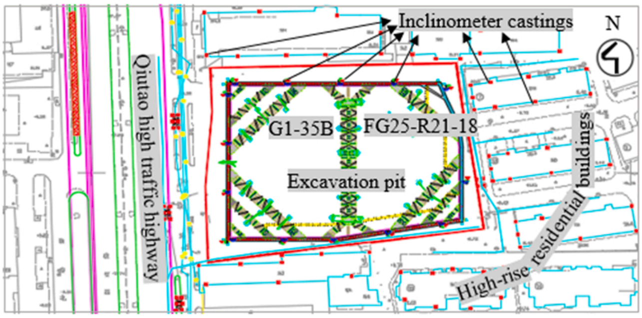

Fig. 1. Triumph Unit project plan view showing the excavation pit, surrounding environment, and the inclinometer points for monitoring purpose.

displacement and bending moment during the soil excavation process for the adjacent facilities' safety considerations.

2. Triumph Unit building project field construction site deep basement excavation support structure construction methodology

The actual field construction site case study application of steel material servo enhanced support system is a deep foundation pit of Triumph Unit, FG25-R21-18 plot Jing-fang demolition resettlement house and the west side G1–35B park green space project in Jianggang district, Hangzhou city, Zhejiang province, China. This case is preferred for analysis because it gives a first-hand information of the stage-by-stage strict application of the steel material servo enhanced support method. The project foundation pit basement area is 2334.5 m^2, and is surrounded by high-rise residential buildings and high traffic highway. Fig. 1 shows the project construction site location plan view. The building block excavation pit is a three-story basement and the excavation depth of the basement is 14.20 m. The building block basement construction processes are divided into 5 stages. The required construction activities at each stage are detailed in Table 1.

With the strict requirement for protection of project site surroundings, Hangzhou Design Institute which is responsible for this project execution, stipulated the project construction standards. The stipulated project construction standards specified the required warning limit for support structure lateral displacement and bending moment at each construction excavation stage. The warning limit of lateral displacement and bending moment during the construction stage 1 is stipulated to not exceed 3.50 mm and 25.00 kN-m respectively. During the construction stage 2, the maximum lateral displacement and bending moment should not exceed 6.50 mm and 170.00 kN-m respectively. The stipulated allowable limits for maximum lateral displacement and bending moment for the construction stage 3 are 10.50 mm and 310.00 kN-m respectively. During the construction stage 4, the maximum allowable limits are 35.00 mm and 600.00 kN-m for lateral displacement and bending moment respectively. In the last construction stage 5, the stipulated allowable limits for lateral displacement and bending moment are the same as those in construction stage 4.

2.1. Basement excavation pit earth retaining structure construction

The basement excavation pit earth retaining structure construction includes the thermal-reactive diffusion (TRD) interpolated H700 steel material pile wall. The pile wall has a maximum depth of 29.50 m. The pile material type is the section steel. The section steel grade is Q235, and its parameter is HN700 × 300. The section steel's tensile, compression, shear, and bending resistance is 215 MPa. The steel plastic development coefficient is 1.05. The basement excavation pit depth is 14.20 m. The embedded depth is 15.30 m. The excavation pit top elevation is ± 0.00. Fig. 2 shows the basement excavation pit support structure cross-section view which depicts the support plane, the water head, 20 kN working load, and the soil strata. Moreover, for geotechnical conditions, the soil stratum at the project construction site is primarily of soft silt with silty clayey properties. This is according to the laboratory test results as presented in Fig. 2, which reveal the project site soil parameter layers' name, depth, unit weight γ in kN/m^3, cohesive force c in kPa, stiffness E_{ur} in kN/m^2, internal friction angle φ in °, and the unit less Poisson ratio v, within the first 29.50 m steel pile retaining wall soil depth.

2.2. Basement excavation pit internal support system construction

Three steel bracing material levels are constructed as the basement excavation internal support structure. The steel bracing material specification is Φ800 * 16 steel tube straight support, and is horizontally spaced 10 m apart at each excavation elevation. The steel bracing vertical spacing is 1.60 m, 4.50 m, and 3.50 m respectively as demonstrated in Fig. 2. All the three steel bracing supports are preloaded with 300 kN axial load capacity. The steel material stiffness is 500 MN/m. Its material resistance is 9000 kN, and the

Table 1
Basement excavation pit support structure construction stages and the construction activities at each stage.

Construction stage number	Activity	Depth (m)
1	Excavation process	-2.10
	Install the first steel material support	-1.60
	Add and optimise the servo load to the first steel material support	-1.60
2	Excavation process	-6.60
	Install the second steel material support	-6.10
	Add and optimise the servo load to the second steel material support	-6.10
3	Excavation process	-10.10
	Install the third steel material support	-9.60
	Add and optimise the servo load to the third steel material support	-9.60
4	Excavation process to basement formation level	-14.20
5	Add a rigid hinge	-12.90
	Dismantle and remove the third steel material servo enhanced support	-9.60
	Add a rigid hinge	-8.95
	Dismantle and remove the second steel material servo enhanced support	-6.10
	Add a rigid hinge	-5.15
	Dismantle and remove the first steel material servo enhanced support	-1.60

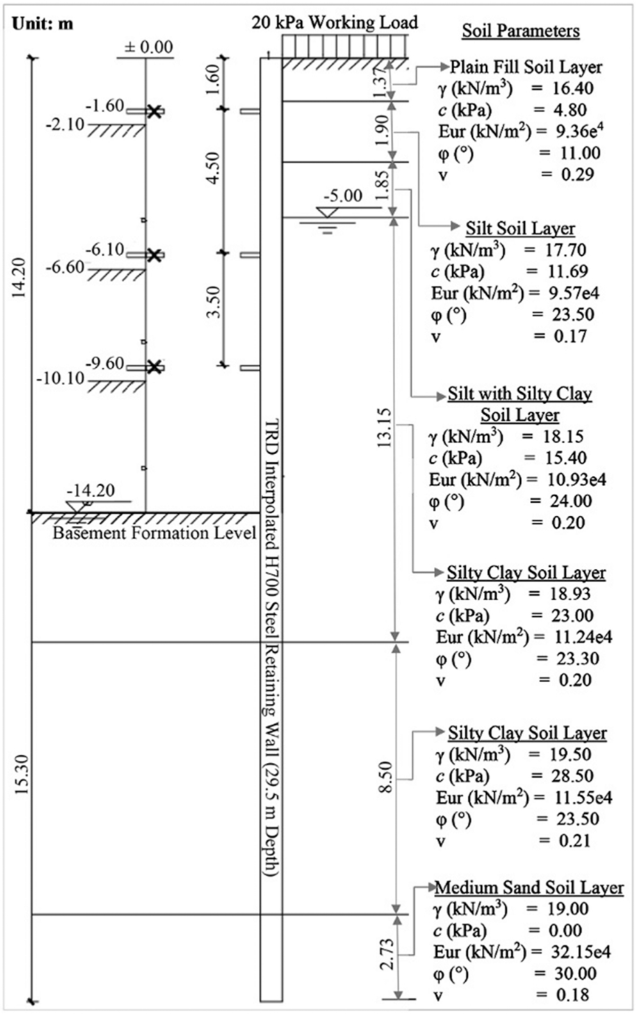

Fig. 2. Triumph Unit building block basement excavation pit cross-section view.

adjustment coefficient is 1.00. The steel bracing internal supports have movable ends for prestress application and are erected at − 1.60 m, − 6.10 m, and − 9.60 m excavation elevations. The steel bracing support at each erection stage is incorporated with the hydraulic servo system to enhance the steel material lateral support mechanism.

Different hydraulic servo system axial loading capacities are added to the 300 kN preloaded steel bracing material supporting the excavated pit wall at each steel erection level during the basement construction process. This is because the steel bracing support structure carries loads instantly after erection [8]. Another method of application is when the steel bracing material is at the verge of reaching its elastic limit, the servo system is activated to increase the load carrying capacity of the lateral steel support system. Fig. 3 shows the field construction site application arrangement and the working principle of the steel material servo enhanced support system linked to a computerised control system.

Servo system comprises of an automatic controlling computerised unit and a hydraulic module. Hydraulic module contains the hydraulic jack together with the hydraulic pump station. Hydraulic jack contains an adjustable connector which is set between the basement excavation pit wall and the end of the steel bracing material. Hydraulic pump station has a pressure transmitting system. The pressure transmitting system is connected to a computerised unit where the servo axial load is added to a predefined value. Then, the combined servo and preloaded steel bracing axial load is automatically increased to support the lateral loads. When a comparison is made with steel bracing material support alone, the steel material servo enhanced support system increases the steel support stiffness and axial loading capacity.

The servo support system application has some drawbacks however. The timing of loading of servo steel bracing is based on engineers' project site experience [10]. If the load is applied after the steel material has passed the ultimate loading stage, then the effect of the servo at that particular steel erection stage will not be optimised and the expected capacity may not be reached. The control effect of stage-by-stage steel material servo enhanced support system application on actual excavation lateral displacement and bending moment is not comprehensive [8,12]. This is because of the limited field construction site application of the steel material

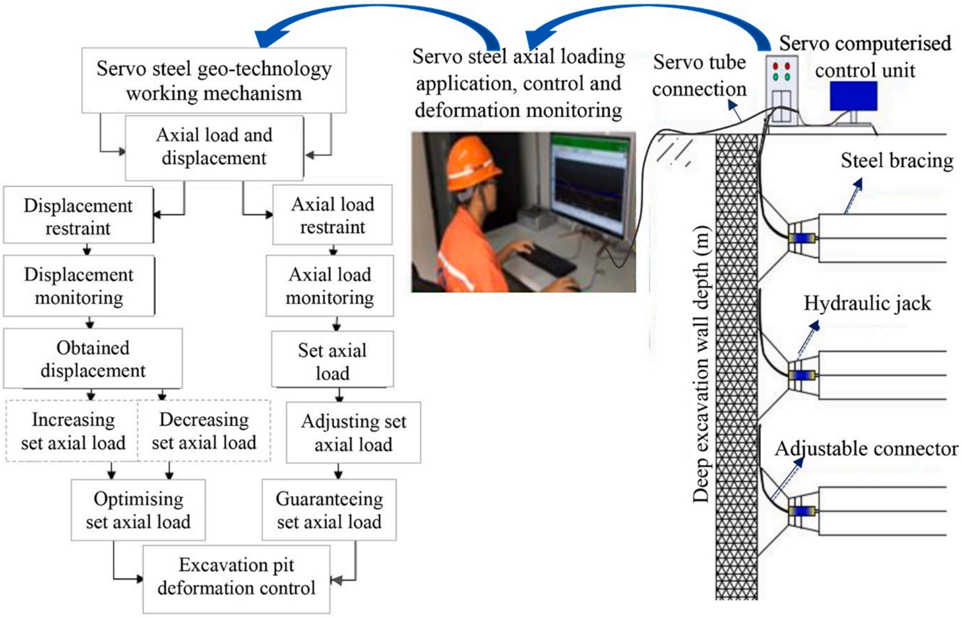

Fig. 3. Field construction site application arrangement showing the working principle of steel material servo enhancement system.

servo enhanced system [11]. Nonetheless, the application of the servo system gives the added advantage of reducing self-weight of the steel material support system. Hence, this study enumerates the usefulness of the addition of a hydraulic servo system to the lateral steel material support system to improve the lateral load resistance of the steel support members on relative lateral displacement and bending moment at an actual excavation site.

3. Analysis of project field results and discussions

In this study, the field data analysis of the Triumph Unit basement excavation involves the evaluation of earth pressure distribution across the ground and controlling of the lateral displacement and bending moment of the earth retaining support structure. The control effect analysis of the lateral displacement and bending moment at each basement excavation stage is performed chronologically by following the Table 1 basement construction stages exclusively.

3.1. Construction stage 1

During the construction stage 1, the project basement excavation process commences. The excavation process is carried out to − 2.10 m stage. The warning value of the lateral displacement and bending moment is limited to not exceed 3.50 mm and 25.00 kN-m respectively according to the project design institute stipulated acceptable requirements. Fig. 4a shows the measured results due to the excavation process commencement to − 2.10 m stage. The negative value in the figure indicates lateral displacement or bending moment inside the retaining wall. The positive value depicts lateral displacement or bending moment outside the retaining wall.

From Fig. 4a, due to the commencement of excavation process to − 2.10 m stage, the earth pressure increases linearly with the retaining wall depth. It increases below the excavated area with 183.91 kN/m maximum. The maximum earth pressure outside the excavated pit wall is 176.77 kN/m maximum. Similarly, the lateral displacement increases inside the pit wall with 5.11 mm maximum at the top of the retaining wall. The lateral displacement outside the wall increases minimally to 0.03 mm. The bending moment inside the wall is 18.37 kN-m. The bending moment outside the wall becomes 50.07 kN-m maximum.

It can be noticed from Fig. 4a measurements that the lateral displacement and bending moment of the pile wall increase with the initial excavation process. This increase can be mainly attributed to the presence of adjacent high-rise buildings and a high traffic highway, thereby influencing the ground surface movement which leads to the distribution of pressure across the ground [14]. The ground pressure redistributes the initial stress of soil, causing inclination, surface subsidence, horizontal dislocation, and curvature change, hence leading to lateral displacement and in return bending moment increase [14]. Moreover, the measured lateral displacement and bending moment exceed the project allowable limits as demonstrated in Fig. 4a. Therefore, the 300 kN preloaded steel bracing material support is erected at − 1.60 m elevation to minimise the lateral displacement and bending moment influenced by the initial soil excavation process.

Fig. 4b shows the obtained results with respect to the erection of the 300 kN preloaded steel material bracing support at − 1.60 m elevation. The earth pressure remains unaffected at 183.91 kN/m and 176.77 kN/m inside and outside the wall respectively. The lateral displacement minimises from 5.11 to 5.02 mm inside the wall. The lateral displacement outside the wall remains unchanged at

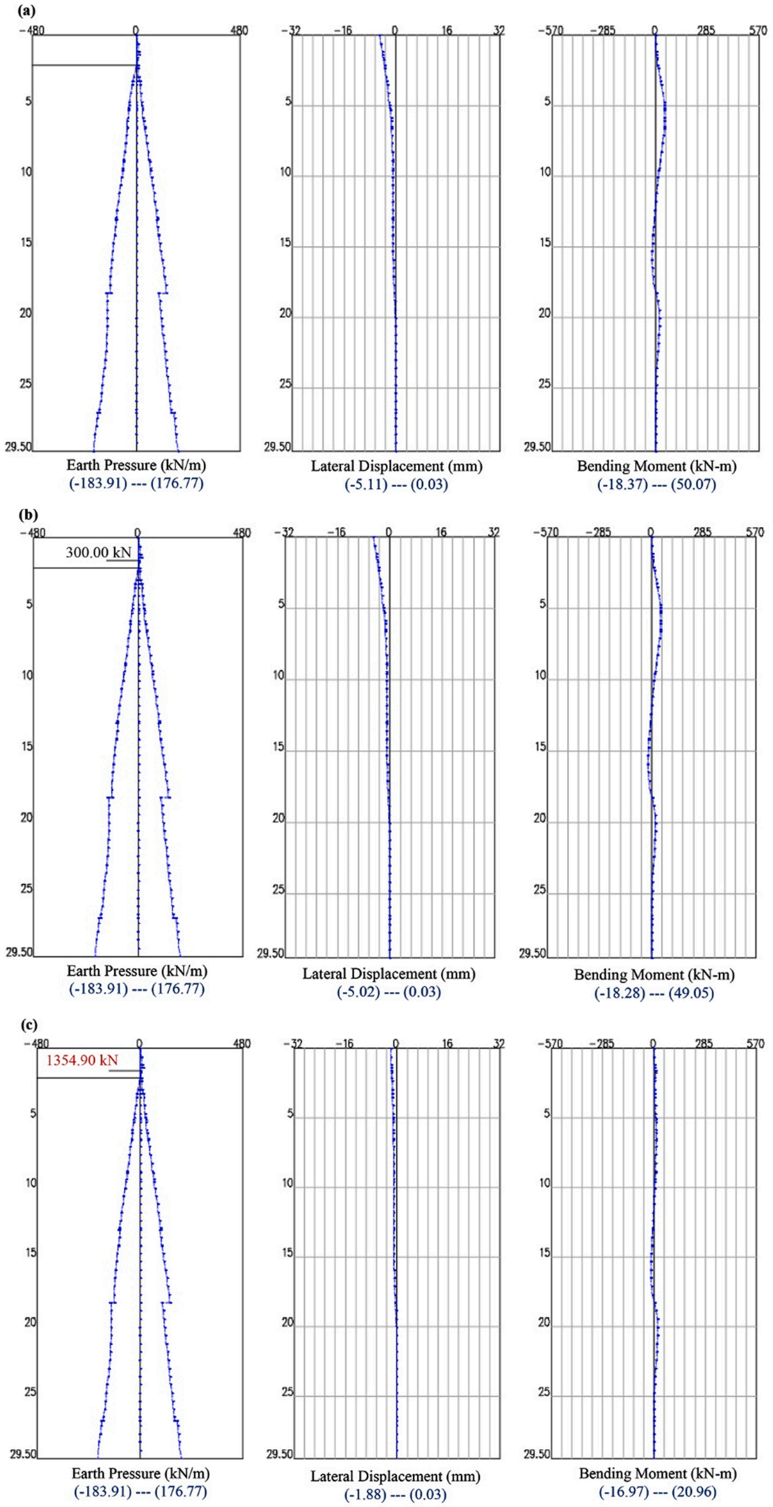

Fig. 4. Construction stage 1 showing the maximum lateral displacement and bending moment: (a) Excavation (− 2.10 m), (b) First steel bracing support (− 1.60 m), and (c) Servo axial loading capacity enhancement (− 1.60 m).

0.03 mm. The bending moment inside the wall declines from 18.37 to 18.28 kN-m. The bending moment outside the wall drops from 50.07 to 49.05 kN-m.

From Fig. 4b, after the erection of 300 kN preloaded steel bracing material support alone at − 1.60 m elevation, the lateral displacement and bending moment have reduced with a minimal degree. This minimal reduction confirms the finding of Wu et al. [3] which depicts that the steel material support alone is effective for lateral support of shallow excavations. When estimated and applied appropriately, steel bracing material support alone in shallow foundation reduces excavation-induced deformation as required [3].

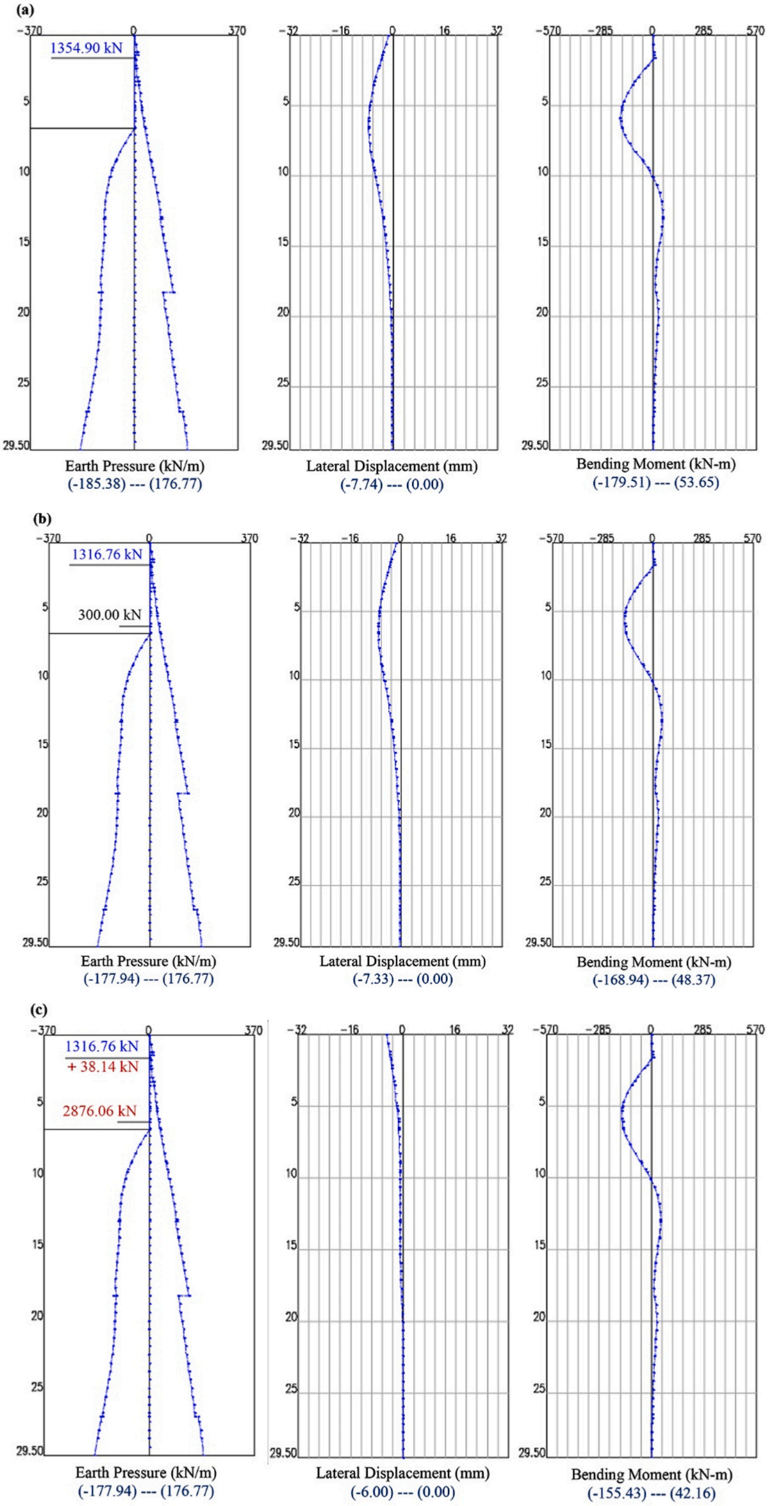

Fig. 5. Construction stage 2 showing maximum lateral displacement and bending moment: (a) Excavation (− 6.60 m), (b) Second steel bracing support (− 6.10 m), and (c) Servo axial loading capacity enhancement (− 6.10 m).

However, the measured results in Fig. 4b exceed the allowable limits at construction stage 1. This leads to the addition of 1054.90 kN servo axial loading capacity to the steel bracing lateral support at − 1.60 m elevation. The addition of servo axial loading capacity determination is based on the project design institute construction experience [7,10]. The total lateral support loading capacity at

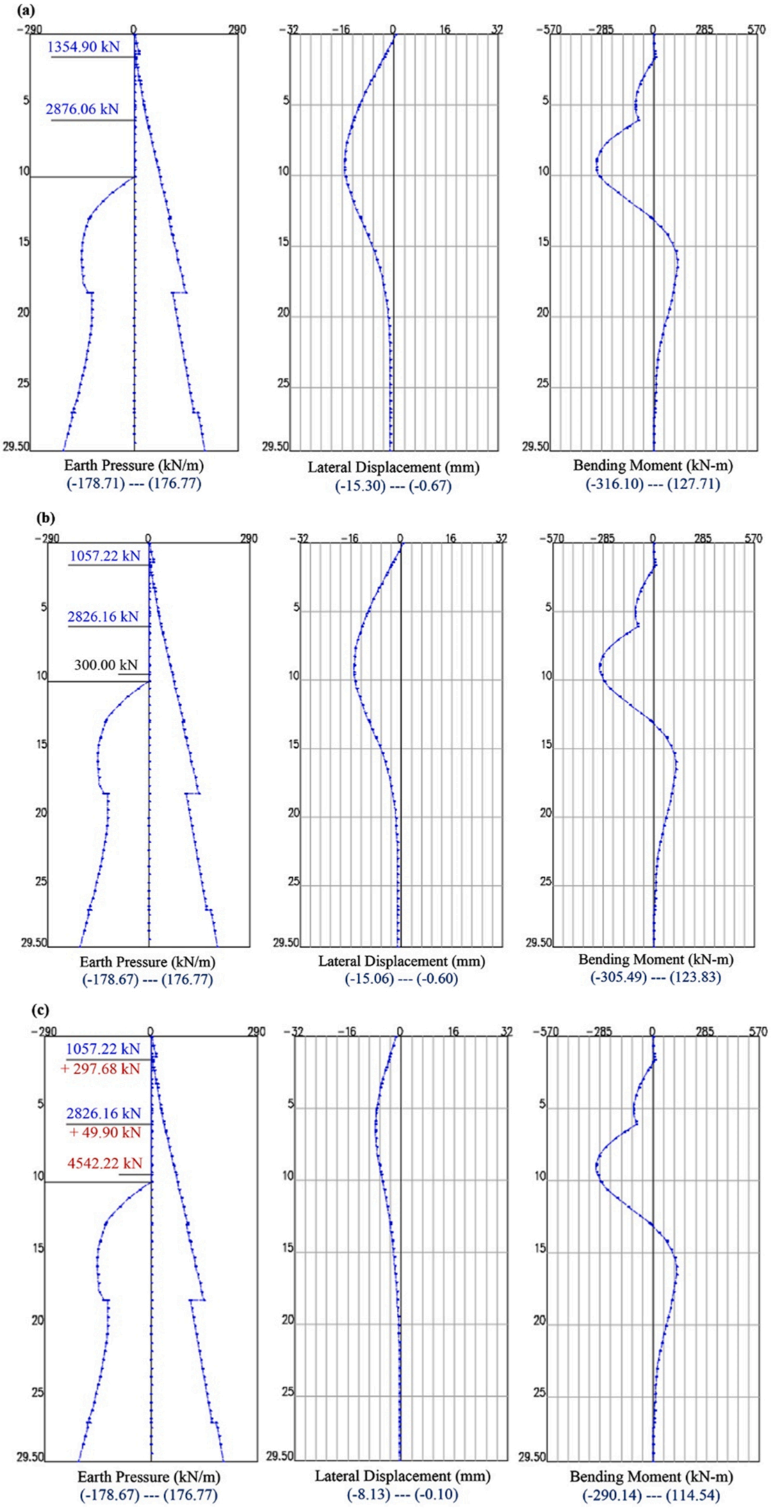

Fig. 6. Construction stage 3 showing maximum lateral displacement and bending moment: (a) Excavation (− 10.10 m), (b) Third steel bracing support (− 9.60 m), and (c) Servo axial loading capacity enhancement (− 9.60 m).

− 1.60 m elevation then becomes 1354.90 kN.

Fig. 4c shows the obtained results after the 1054.90 kN servo loading capacity enhancement at − 1.60 m stage. The earth pressure remains unaffected at 183.91 kN/m and 176.77 kN/m inside and outside the wall respectively. The lateral displacement inside the wall declines remarkably from 5.02 to 1.88 mm. The lateral displacement outside the wall remains stable at 0.03 mm. The maximum bending moment inside and outside the wall reduces from 18.28 to 16.97 kN-m and from 49.05 to 20.96 kN-m respectively.

As noticed from Fig. 4c measurements, the results satisfy the limit of lateral displacement and bending moment at the construction stage 1 as required by the project after the servo axial loading capacity addition to the steel bracing material support. The great reduction in lateral displacement and bending moment with respect to the addition of servo axial loading capacity to the steel bracing material support confirms the finding of Ming-Guang et al. [10]. In their numerical simulation study, Ming-Guang et al. [10] shows the effectiveness of steel material servo enhanced axial loading support application on lateral displacement and bending moment control during excavation process.

3.2. Construction stage 2

During construction stage 2, the excavation process is advanced to − 6.60 m stage. The servo steel enhanced axial load support of 1354.90 kN is optimised and maintained at − 1.60 m elevation. The stipulated acceptable requirements during the construction stage 2 for the maximum lateral displacement and bending moment are 6.50 mm and 170.00 kN-m respectively. Fig. 5a shows the obtained results after the excavation process advancement to − 6.60 m stage. The earth pressure below the excavated pit area rises from 183.91 kN/m to 185.38 kN/m maximum. The earth pressure outside the wall remains unaffected at 176.77 kN/m maximum. The lateral displacement inside the wall increases exceedingly from 1.88 mm to 7.74 mm maximum. The lateral displacement outside the wall increases towards the inside of the wall from 0.03 to 0.00 mm. The maximum bending moment inside the wall increases from 16.97 to 179.51 kN-m, and the maximum bending moment outside the wall gets to 53.65 kN-m from 20.96 kN-m.

It can be noticed from Fig. 5a that the obtained results exceed the project allowable limits at construction stage 2. Moreover, with the advancement of excavation process to − 6.60 m stage, the steel material servo enhanced support at − 1.60 m elevation losses 38.14 kN axial loading capacity. The basement excavation support loading capacity at − 1.60 m elevation drops to 1316.76 kN from 1354.90 kN. This phenomenon of losing axial loading capacity of the steel material servo combined support system was also reported in a study done by Di et al. [7] which shows the loss in axial loading capacity of steel material servo-combined support members as basement soil excavation process is progressed to a deeper elevation.

The second 300 kN preloaded steel bracing material internal support structure is erected at − 6.10 m elevation to further reduce the lateral displacement and bending moment incurred due to the advancement of excavation process to − 6.60 m stage. The total support load then becomes 1316.76 kN at − 1.60 m elevation and 300 kN at − 6.10 m elevation. Fig. 5b shows the obtained results after the support structure erection. The maximum earth pressure remains unaffected at 177.94 kN/m and 176.77 kN/m inside and outside the wall respectively. The maximum lateral displacement inside the wall reduces minimally from 7.74 to 7.33 mm. The lateral displacement outside the wall remains stable at 0.00 mm. The maximum bending moment drops from 179.51 to 168.94 kN-m inside the wall. The bending moment outside the wall declines minimally from 53.65 to 48.37 kN-m. It can be observed from Fig. 5b that the lateral displacement and bending moment measurements exceed the stipulated project standards at construction stage 2.

This leads to the incorporation of higher servo loading capacity of 2576.06 kN at − 6.10 m steel erection stage, and the enhancement of the 38.14 kN lost axial loading capacity at − 1.60 m elevation using the hydraulic servo method. Then the total axial load lateral support becomes 2876.06 kN at − 6.10 m elevation. The servo steel support loading at − 1.60 m is restored to 1354.90 kN capacity. Fig. 5c shows the obtained results after the servo steel support loading enhancement. The maximum earth pressure remains stable at 177.94 kN/m and 176.77 kN/m inside and outside the wall respectively. The lateral displacement further reduces from 7.33 to 6.00 mm inside the wall. The lateral displacement outside the wall remains unchanged at 0.00 mm. The bending moment drops from 168.94 to 155.43 kN-m inside the wall. The bending moment outside the wall declines from 48.37 to 42.16 kN-m.

It can be remarked from Fig. 5c that the obtained lateral displacement and bending moment meet the limit of project requirements at construction stage 2. The remarkable result of satisfying the acceptable limit at construction stage 2 can be attributed to the addition of higher servo support loading capacity to the preloaded steel material support at − 6.10 m elevation and also the restoration of the lost steel servo combined axial loading capacity at − 1.60 m elevation.

3.3. Construction stage 3

The soil excavation process is progressed to − 10.10 m stage during the construction stage 3. The steel material servo enhanced loading capacity supports of 1354.90 kN and 2876.06 kN are optimised and maintained at − 1.60 m and − 6.10 m elevations respectively. The stipulated acceptable requirements during construction stage 3 for lateral displacement and bending moment are 10.50 mm and 310.00 kN-m respectively. Fig. 6a shows the obtained results after the advancement of the excavation process to − 10.10 m stage. The maximum earth pressure below the excavated pit area minimally increases from 177.94 to 178.71 kN/m. The earth pressure outside the wall remains unaffected at 176.77 kN/m. The lateral displacement inside the wall doubles from 6.00 to 15.30 mm maximum. There is no lateral displacement outside the wall. The lateral displacement of 0.00 mm outside the wall moves to the inside of the wall by 0.67 mm at the retaining wall bottom. The maximum bending moment inside the wall doubles from 155.43 to 316.10 kN-m. The bending moment outside the wall triples from 42.16 to 127.71 kN-m.

From Fig. 6a, the obtained results exceed the project stipulated allowable limits at construction stage 3, and the lateral displacement and bending moment increase with excavation depth increase. The steel material servo enhanced support at − 1.60 m elevation losses 297.68 kN axial loading capacity. The steel material servo enhanced support at − 6.10 m elevation also experiences loss in axial loading capacity of 49.90 kN. This loss in steel material servo combined support axial loading capacity mainly resulted from the progression of soil excavation to − 10.10 m stage. This phenomenon was also determined by Di et al. [7]. Thus, the support loading capacity at − 1.60 m and − 6.10 m elevations drops to 1057.22 kN and 2826.16 kN respectively.

Then the third 300 kN preloaded steel support is erected at − 9.60 m elevation to further reduce the lateral displacement and bending moment influenced by the soil excavation process to − 10.10 m stage. This brings the total lateral support loading capacity at − 1.60 m, − 6.10 m, and − 9.60 m elevations to 1057.22 kN, 2826.16 kN, and 300 kN respectively. Fig. 6b shows the obtained results. The maximum earth pressure remains unaffected at 178.67 kN/m and 176.77 kN/m inside and outside the wall respectively. The maximum lateral displacement inside the excavated pit wall reduces minimally from 15.30 to 15.06 mm. There is no lateral displacement outside the wall. However, the minimum lateral displacement of 0.67 mm inside the wall reduces to 0.60 mm. The maximum bending moment drops from 316.10 to 305.45 kN-m inside the wall. The bending moment outside the wall declines minimally from 127.71 to 123.83 kN-m. Furthermore, it can be observed from Fig. 6b that the measurements exceed the stipulated project lateral displacement and bending moment requirements.

This leads to the addition of higher servo loading capacity of 4242.22 kN at − 9.60 m elevation to enhance the internal steel support loading capacity at − 9.60 m elevation. The lost axial loading capacities of 297.68 kN at − 1.6 m elevation and 49.90 kN at − 6.10 m elevation are respectively restored via the computerised servo control station unit [10]. Then the total lateral support axial loading capacity is kept at 1354.90 kN at − 1.60 m elevation, 2876.06 kN at − 6.10 m elevation, and 4542.22 kN at − 9.60 m elevation.

Fig. 6c shows the obtained results after the servo support axial loading capacity enhancement. The maximum earth pressure remains stable at 178.67 kN/m and 176.77 kN/m inside and outside the wall respectively. The maximum lateral displacement inside the wall declines remarkably from 15.06 to 8.13 mm. There is no lateral displacement outside the wall. However, the minimum lateral displacement of 0.60 mm inside the wall reduces to 0.10 mm. The maximum bending moment drops from 305.49 to 290.14 kN-m inside the wall. The bending moment outside the wall declines from 123.83 to 114.54 kN-m.

It can be remarked from Fig. 6c that the obtained results satisfy the limit of project requirements at construction stage 3 after the higher servo axial loading capacity enhancement and the restoration of the lost servo steel support axial loading capacities. The obtained results corroborate the numerical simulation results of Fang et al. [12] which discuss the advantage of employing higher servo axial loading capacities in basement excavation-induced deformation control.

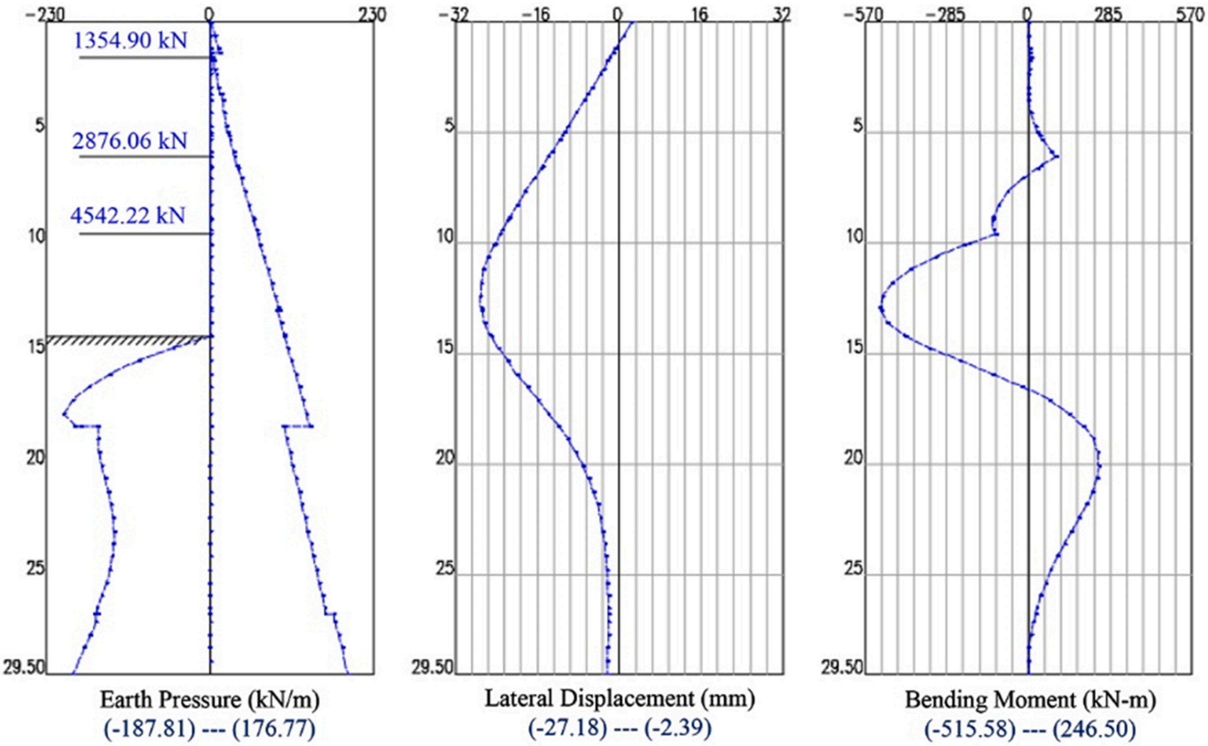

Fig. 7. Construction stage 4 showing the maximum lateral displacement and bending moment during excavation to the basement formation level (− 14.20 m).

3.4. Construction stage 4

During construction stage 4, the excavation process is advanced to − 14.20 m basement formation level. The steel material servo enhanced system axial loading support of 1354.90 kN, 2876.06 kN, and 4542.22 kN remains maintained at − 1.60 m, − 6.10 m, and − 9.60 m elevations respectively. The maximum allowable limits at this construction stage are 35.00 mm and 600.00 kN-m for the lateral displacement and bending moment respectively.

Fig. 7 shows the obtained results during the construction stage 4 due to the advancement of the excavation process to − 14.20 m formation level. The earth pressure below the excavated pit area increases from 178.67 to 187.81 kN/m maximum. The earth pressure outside the wall remains unchanged at 176.77 kN/m maximum. The lateral displacement inside the wall triples from 8.13 to 27.18 mm maximum. There is no lateral displacement outside the wall. However, the minimum lateral displacement of 0.10 mm inside the wall increases to 2.39 mm. The maximum bending moment inside the wall increases from 290.14 to 515.58 kN-m, and the bending moment outside the wall doubles from 114.54 to 246.50 kN-m.

It can be remarked form Fig. 7 that the obtained results are kept within the project allowable limits at construction stage 4. This shows that the combined steel material servo support system has played a good basement excavation pit support role. The larger the steel material servo enhanced the axial loading capacity support application in subsequent basement pit elevations, the greater the lateral displacement and bending moment reduction.

3.5. Construction stage 5

This stage involves dismantling and removing of the third, second, and first servo system together with the three preloaded steel bracing internal support structures as chronologically as provided in Table 1. To restrain the lateral displacement and bending moment exhibition during the internal support structure removing process, a rigid hinge is added prior to each steel servo combined support dismantling and removing commencement (Table 1). First, the bottom rigid hinge is added at − 12.90 m level, then the third servo system together with the third preloaded steel bracing support at − 9.60 m elevation is dismantled and removed. To remove the hydraulic servo system, the gap that exist between the end of the steel bracing support and the retaining wall is inserted with a wedge, and the servo system hydraulic jack is dismantled and removed together with the steel bracing material support structure [10].

This process is followed by the addition of a second rigid hinge at − 8.95 m level. Then the second servo system and the preloaded steel bracing support at − 6.10 m elevation are dismantled and removed. The last rigid hinge is then added at − 5.15 m level. This is succeeded by dismantling and removing of the first servo system together with the preloaded steel bracing support at − 1.60 m elevation.

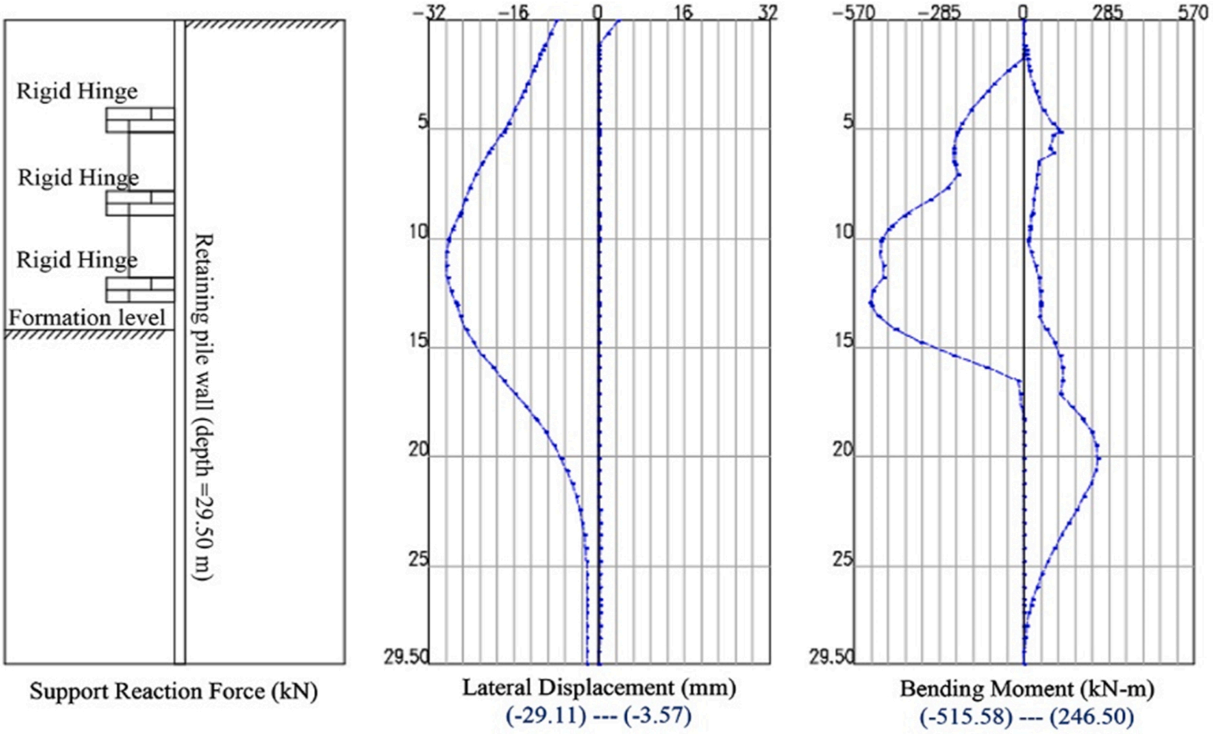

Fig. 8. Construction stage 5 showing the envelope diagram of the measured maximum lateral displacement and bending moment at the completion of project basement construction works.

After the internal support structure is completely removed, the induced basement excavation pit lateral displacement and bending moment are again checked to ensure that they do not exceed the project stipulated allowable limits at construction stage 5. The stipulated allowable limits during construction stage 5 are the same as those during construction stage 4. The maximum lateral displacement and bending moment should not exceed 35.00 mm and 600.00 kN-m respectively.

Fig. 8 shows the envelope diagram of the obtained lateral displacement and bending moment after the addition of the rigid hinges and the removal of the internal support system. The lateral displacement inside the wall increases from 27.18 to 29.11 mm maximum. There is no lateral displacement outside the wall. However, the minimum lateral displacement of 2.39 mm inside the wall increases to 3.57 mm. The maximum bending moment remains stable at 515.58 kN-m and 246.50 kN-m inside and outside the wall respectively.

It can be shown from Fig. 8 that the lateral displacement and bending moment have increased with a minimal degree. This minimal increase can be attributed to the internal support structure dismantling and removing processes at the construction site [14]. Nonetheless, the obtained lateral displacement and bending moment satisfy the project acceptable limit requirements at construction stage 5. This shows that the incorporation of rigid hinges, prior to the stage-by-stage steel material servo combined support dismantling and removing process, maintained the lateral displacement and bending moment within the project requirements at construction stage 5. This determination confirms the proposition by Xu et al. [14] which suggests the stage-by stage addition of rigid hinge support during basement steel support structure dismantling and removing process. The stage-by-stage addition of rigid hinge support prior to excavated pit wall internal steel support removal process maintains the deformation within a required limit [14,15].

Compared with the servo numerical simulation application results from previous studies, the obtained field results at Triumph Unit construction site corroborate well with the measured numerical results of Di et al. [7], Ming-Guang et al. [10], and Sun [13]. Specifically, Ming-Guang et al. [10] study restrained the maximum wall displacement and bending moment to 95 mm and 650 kN-m respectively of a 19.7 m deep basement excavation pit. This was achieved after application of 1745 kN, 2688 kN and 4971 kN steel servo combined load capacities at the first, middle, and final excavation stages respectively. Similarly, a research conducted by Di et al. [7] observed that a 24.8 m deep excavation pit which was supported with a steel material servo enhanced system managed to control the wall displacement and bending moment to meet the limit of 40 mm and 800 kN-m respectively as required by the project. This was achieved in comparison with the measurements of the section of the same pit which was supported with steel bracing material without servo enhancement. In their conclusion, Di et al. [7] stated that the incorporation of higher servo loading support capacity of more than 2131.5 kN during excavation controlled the wall displacement and bending moment efficiently. A study conducted by Sun [13] concluded that employing higher servo axial loading support capacity during the excavation process leads in greater retaining wall displacement and bending moment reduction compared with employing steel bracing material support alone.

Moreover, Fig. 9 shows the Triumph Unit building block basement excavation project simulated PLAXIS three dimension (3D) support plane maximum displacement result of 29.75 mm. The simulated project maximum displacement result is consistent with the obtained field project construction site maximum lateral displacement result of 29.11 mm at the completion of the project basement execution works during construction stage 5. Moreover, the field project construction results agree well with the present and previous numerical literature studies. They all demonstrate the strong control effect of steel material servo enhanced support system stage-by-stage application on lateral displacement and bending moment to the actual deep basement excavations.

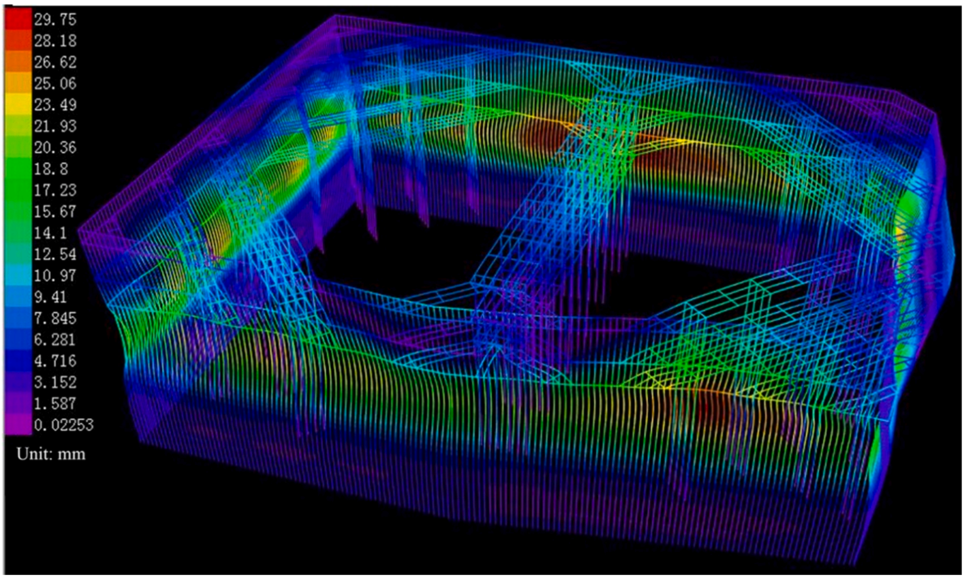

Fig. 9. Triumph Unit PLAXIS 3D simulated support plane maximum displacement development profile during the excavation process.

4. Conclusion

In this study, the Triumph Unit high-rise building block stage-by-stage basement construction process has served as the practical application of the steel material servo axial load enhancement system on the actual excavation site. The main work is summarized as follows:

1) At the Triumph Unit high-rise building basement project, the servo axial loading capacities were applied and adjusted directly to the preloaded steel bracing support system at the construction site during the construction process.
2) Servo steel material enhanced deep basement internal support application was able to increase the load carrying capacity of the support structures at various levels of excavations. The stiffness of the support structure was increased by the application of the hydraulic servo.
3) With the application of steel material combined servo loading capacities, the lateral displacement and bending moment during excavation process are kept within the limit as required at each respective construction stage. Specifically, the maximum lateral displacement and bending moment are 29.11 mm and 515.58 kN-m respectively at the completion of the project construction works.
4) The obtained field results demonstrate that the steel material servo enhanced support is a suitable option for application to actual deep excavation projects with strict displacement and bending moment control requirements. This actual construction application validated previous numerical research works and the project PLAXIS 3D simulated support plane displacement.
5) This research could not substantiate the effect of steel material servo enhanced excavation pit support on the overall basement excavation pit support structure stability check, anti-uplift check, anti-overturning stability check, and anti-seepage stability check. It is recommended that future works should investigate these phenomena to optimise the stage-by-stage steel material servo combined support field construction site application process.

Declaration of Competing Interest

The authors declare that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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