Report 12th IPA Press-in Engineering Seminar in Tokyo 2020

(1) TC1 "Application of Cantilever Type Steel Tubular Pile Wall embedded to Stiff Grounds"

Jiro Takemura

Associate Professor, Tokyo Institute of Technology Director, IPA / Chair, TC1

IPA-Technical Committee (TC)1 (Chaired by Dr. Jiro Takemura, the author) was set up in 2017 to figure out the issues for further application of cantilever type steel tubular pile wall embedded to stiff grounds and establish a rational design procedure of embedded cantilever steel tubular pile wall as the final goal. This report overviews the research activities done by TC1, i.e., case study, physical modeling, numerical analyses, parametrical study by design models, which were presented in the seminar.

1. Background and objectives

Thanks to the innovative pile installation method, like rotary cutting press-in method (e.g., Gyropress), the applicability of steel tubular pile walls (STPW) retaining systems has increased significantly for various structures (road, harbor, railway) and objectives, not only ordinary retaining structures (Miyanohara et al., 2018, Suzuki and Kimura, 2021), but also restoration, rehabilitation and reconstruction of disaster areas (Takada, 2016, He, 2018). The installation ability of large steel tubular pile (STP) into very stiff grounds is a critical advantage of the rotary cutting press-in method. The combination of large diameter and high rigidity STP, and the stiff embedded ground enables to construct cantilever type walls with large retained height (Fig. 1). By the combination, the wall top displacement caused by the wall bending deflection and the wall rotation in the embedment can be controlled below the required displacement. However, the current design method of embedded cantilever wall has been developed for the relatively flexible steel sheet pile wall into soft grounds for small retained height (e.g. less than 4m, JRA (1999)). Therefore, simple application of the current design method to the cantilever type STPW embedded in stiff grounds (Fig. 2) may require unnecessary embedment depth, or increase a risk of failure caused by the unexpected performance of the wall. Several concerns can be pointed out such as,

1) The minimum embedment depth (d_0) requirement using characteristic value (β), such as $d_0 \ge 3/\beta$ (ASP, 2009; IPA,2014&2016) should be verified, as it is based on long flexible wall behavior in an infinite uniform elastic media, which conflicting the rigid nature of large diameter pile;

2) As the pile diameter (Φ) increases, the relative embedment depth (d_e/ Φ) and wall thickness and diameter ratio (t/ Φ) tend to decrease. Furthermore, near the surface of stiff ground, especially rock, the stress concentration could occur on the front side of tubular pile. These particular conditions could enhance local and 3D behavior,



Fig. 1. Application of STPW (H=13m, lp=23m) for road widening projects. (Miyanohara et al.2018)



Fig. 2. Cantilever STPW embedded in stiff ground and conditions used in the design.

which is not taken into account in the conventional 2D analytical/numerical models;

3) High confinement or fixity of the piles by the stiff ground could generate the large resilience of pile, which affects the wall-soil interaction, the wall pressure from the retained soil, and the residual wall displacement after the temporal loading event, e.g., earthquake.

To answer the above-mentioned concerns and establish a rational design procedure, four working groups were created

in TC1 with several tasks as shown below. Note: some findings related to the tasks underlined were presented in the seminar.

- WG1 on design method:

Tasks 1: to analyze present design methods, and identify the issues such as embedment depth, soil characteristics, seismic design.

Task 2: to analyze the design procedure of existing large diameter tubular steel pipe walls.

Task 3: to propose a new rational design method of large diameter tubular steel pipe wall including seismic design. - WG2 on centrifuge model tests:

Task 1: to clarify mechanical behavior of large diameter tubular steel pipe wall in stiff ground under static loads.

Task 2: to analyze influences of critical conditions such as embedment depth, ground stiffness and strength on the wall behavior.

Task 3: to discuss difference between the behavior of actual structures and that predicted by the simplified design model.

Task 4: to simulate the deformation and failure behavior under earthquake loading.

- WG3 on numerical analyses:

Task 1: to verify and calibrate 3D FEM method by centrifuge modeling.

Task 2: to analyze the detail and local behavior of wall and ground, which cannot be observed in the centrifuge model tests.

Task 3: to analyze the influence of parameters on behavior of large diameter tubular steel pipe wall using simple flame analysis and 2D FEM.

- WG4 on case study of construction:

Task 1: to collect construction cases with design details as many as possible.

Task 2: to collect the data observed during and after construction, if available, with the collaboration of TC2.

Task 3: to identify the concerns in the actual construction, in particular on the cost and time.

2. Case study

Since the Gyropress method was developed by Nippon Steel and GIKEN LTD and first applied in 2004, it has been applied more than 400 projects till 2019 (Hirata & Matsui, 2016; IPA, 2019; Suzuki & Kimura, 2021). Fig. 3 shows some summary of the case records, giving the number of projects in terms of pile diameter, pile length with the joint number and maximum converted SPT N-values with the site ground type. As for the pile diameter, 1m piles have been most commonly used about 40%, but the large diameter piles over 1m have been used more than 30% with 2.0m maximum. The project shown in Fig. 1 is an example of the 2.0m pile wall. While for the pile length, the most frequently used length is about 18m and very long piles over 30m were constructed. The number of welding joint depends on the site condition, such as upper space clearance, and the required pile length. The most of piles have been embedded in the ground with maximum N value over 50. About 20 % of recorded cases, the walls were constructed in gavel or rock ground with the converted N-value of 300 or higher. The application of large diameter pile in the stiff grounds for large height retaining walls is an increasing trend especially for the site with severe conditions, such as spatial restriction, low noise and vibration requirements, and short construction period.

Among the records of which design procedure were confirmed, the minimum embedment depth $(d_0 \ge 3/\beta)$ were adopted especially for the road construction projects. Although the number of applications has increased significantly, very limited record is available on the monitored behavior of the wall during and after the construction. The data related to serviceability limit state (SLS) and the ultimate limit state (USL), and the wall performance from SLS and ULS under various actions, e.g., static and seismic loadings are critically important to rationalize the design procedure.



Fig. 3. Summary of case records of STPW installed by rotary cutting press-in method. (Suzuki & Kimura, 2021)

3. Behavior of large diameter STPW investigated by physical models and numerical models

To fill the gap or limitation of field records and investigate the critical behavior of large diameter STPW embedded in stiff grounds, several series of centrifuge model tests and numerical analyses have been carried out to discuss the effects of critical conditions, such as embedment depth, and ground conditions, 3D effect of tubular pile wall, and static and dynamic loading.

(1) Centrifuge model study

Three series of centrifuge model tests were conducted, 1) Simulation of excavation and loading using cantilever plate wall embedded in soft rock (Kunasegaram et al., 2018 and Kunasegaram & Takemura, 2019), 2) Horizontal loading tests to single STP pile and STP wall socketed in a soft rock with and without overlying sand, and 3) Dynamic loading tests to STPW in a soft rock. The main parameter studied is the socket depth to the stiff layer (d_r). For the uniform soft rock ground, the wall embedment depth (d_e) is equal to d_r, while for the two-layers ground d_e is the sum of the top layer depth and d_r (Fig. 2). To generalize the embedment or socket depth, normalized embedment depth (d_e β or d_r β) were estimated. The d_e and d_r adopted in the centrifuge tests were all far below the minimum embedment depth (d₀=3/ β).

a) Series I model: 2D retaining wall

Model test setup shown in Fig. 4 can simulate an excavation process and an extreme loading for a cantilever type retaining wall in a geotechnical centrifuge. In other words, it can model the high stiffness wall behavior with large retaining height from the serviceability limit state (SLS) to the ultimate limit state (ULS). In this series, several centrifuge model tests were conducted on plate walls with per width flexural rigidity (EI) equivalent to STPW with Φ =2.5m and 1.0m, embedded in soft rocks and sand (Kunasegaram et al., 2018; Kunasegaram & Takemura, 2019). Observed wall top displacements and rotations of 12m high rigid walls (Φ_{eq} =2.5M) with d_e =2.5m ($d_e\beta$ =0.86) and 3.0m ($d_e\beta$ =1.05) are compared in Fig. 5. As a unified loading index in the two processes, the moment load applied at the excavation bottom is used in the horizontal axis. Though $d_e\beta$ s are much smaller than the minimum requirement ($d_0\beta$ =3), the wall displacements by the excavation were well controlled below the target allowable displacement (δ_t =50mm, 0.4% wall height). Assuming ULS at δ_t =5%H, the safety margin at SLS against the failure are about threefold in terms of the moment load. Backward slip failure was confirmed for d_e =2.5m wall after the test, but for d_e =3.0m wall, the embedment portion was securely fixed by the soft rock, preventing the catastrophic failure. A half meter increment of the embedment for this case can significantly increase the safety of the wall.







Fig. 4. Centrifuge model test setup on rigid plate wall (Kunasegaram & Takemura, 2019).



b) Series II model: parametric study on rock sock depth and ground conditions To investigate the effect of embedment depth under clear loading conditions, lateral loading tests were performed for Φ =2.0m single STP (SP) and STP wall (RPW) socketed in the soft rock with and without overlying sand. The load – displacement curves are compared in Fig. 6. Details of the tests are given in Kunasegaram et al. (2019), but the test conditions, e.g., ground conditions and socket depth with normalized depth [d_r, d_r β] are shown in the figure. From Series II tests, several findings are derived. 1) Lateral resistances of wall and single pile increase with d_r, but the trend of the increase depends on imposed displacement, ground condition, and types of failure (ground failure or pile failure, Fig. 7). 2) Optimum socket depth, over which the effect of d_r is insignificant is much smaller than 3/ β . 3) As shallow rock part mainly resists to the horizontal load in the early stage of loading, the effect of socket depth may not be so apparent.

However, once the rock initiates yielding at the shallow depth, the influence of socket depth becomes eminent. 4) The single piles have higher lateral resistance per unit width than the walls both for the initial subgrade reaction and the ultimate resistance. 5) The effect of socket depth and the difference between the pile and the wall are more significant for the single soft rock layer than the sand/soft rock layers. 6) In the two layers, the complicated interaction between pile/wall and soil determines the residual displacement and lateral stiffness of wall. The above findings are all critically concerned to the issues for the rational design procedures, such as, critical embedment depth, non-linearity of p-y curves, and accumulation of residual displacement of the wall subjected to various loading history.





Fig. 6. Effect of embedment depth observed in Series II centrifuge tests (Kunasegaram et al., 2019).

Fig. 7. Failure mode observed in wall loading in Series II centrifuge tests (Kunasegaram et al., 2019).

c) Series III model: Dynamic loading on STP retaining wall embedded in soft rock

A 12m high cantilever walls embedded in the soft rock with backfill sand, which is similar to the model in Series I, were made using the same STP wall in Series II. Several dynamic loadings were applied to the models with different embedment depths (Shafi et al., 2021). In the loading sequence, water was fed in the backfill to rise the water level. The accumulated wall displacements observed were plotted against the cumulative Arias intensity for the wall with d_e=2.5m (d_r β =1.2) and 3.0m (d_r β =1.6) in Fig. 8. Similar to Series I, the dynamic stability of the wall is significantly increased by a half meter increase of the embedment into the soft rock. It was also found that high confinement or fixity of the piles by the stiff ground could generate the large resilience of pile, which resulted in the increase of wall earth pressure after shaking. This pressure should be considered as an action to examine the structural safety of the pile and wall residual displacement after the earthquake.

(2) Numerical and analytical studies

Though the centrifuge model tests could provide valuable results on the mechanical behavior of the cantilever type STPW embedded in stiff grounds, there are still many remaining concerns which might affect the wall behavior or be critical in the rational and safe design procedure, such as plugging of rock in the socket part, local 3D effect of deformation of thin wall tubular pile. In particular, the pile structural failure with local buckling (Fig. 7) could be a common ULS for the wall relatively large d_{e_r} even $d_e\beta$ are well below the minimum requirement ($d_0\beta$ =3). Using 3D FEM, Ishihama et al. (2019) investigated the plugging effect, the local stresses at the pile tip, and pile deformation at the pile tip and the rock surface, and found that the plugging effect and 3D effects could not significantly affect the overall behavior of laterally loaded STPW in soft rock. TC1 WG3 further conducted 3D and 2D FEM analyses for the wall model embedded in the soft with d_r=4.0m (Centrifuge test Series II). In the 3D analysis, the actual tubular pile was modeled by solid element, while in the 2D analysis, the pile was modeled by a beam element with equivalent EI of the actual STP wall. The load – displacement curves



Fig. 8. Effect of embedment depth under dynamic loading Series III centrifuge tests (Shafi et al., 2021).



Fig. 9. 2D and 3D FEM results of laterally loaded STPW embedded in soft rock with centrifuge model result: d_r =4m.

obtained by the 3D and 2D analyses were compared with the centrifuge test result in Fig. 9. At the relatively small displacement less than 50mm, which corresponds to allowable value or SLS, no significant difference can be seen in the 3D and 2D models. Over this SLS, the resistance of 2D model becomes larger than that of the 3D model. This can be attributed to local yielding of the ground and pile due to stress concentration at the front toe near the rock surface and back toe near the pile bottom. The analyses overestimate the ultimate resistance, as the FEM cannot simulate the crack formation and back slip failure (Fig. 7). However, from Fig. 9 it can be said that the 2D model can be applied without specific consideration of 3D effects of STPW for the displacement prediction till the SLS.

The top wall displacements analyzed by subgrade reaction method using bi-linear p-y relation is plotted against to the relative embedment depth to the minimum requirement ($d_e\beta/3$) in Fig. 10. This is the common analytical model for the design of retaining wall called "elasto-plastic analysis" in Japan (JRA, 1999). The wall and ground conditions modeled in the centrifuge test Series I were assumed in the analyses, which are indicated in the figure with the centrifuge experiment results. The elasto-plastic analysis could predict the wall defection with reasonable accuracy. From the figure the critical embedment depth, over which the displacement markedly increases can be confirmed. For the soft rock cases, the critical depths are much smaller than the minimum required depth ($3/\beta$), 20 to 30%, especially for the large diameter and high retaining wall. While for sand case the critical depth is about 60% of $3/\beta$. These trends of the d_e effect were also confirmed by rigid-plastic FEM (Mochizuki et al., 2019).



Fig. 10. Result of subgrade reaction methods using bi-linear p-y relation (Ishihama et al., 2018).

4. Toward rational design procedure and practice

Current design practice for the embedded cantilever wall using the minimum embedment depth ($d_0=3/\beta$) adopted in the simple design method (ASP, 2009; IPA, 2014&2016) is based on the assumption of infinite beam on the uniform linear elastic subgrade. But the subgrade reaction of the pile and wall are very non-linear and change with depth. As its simplicity, this simple method could be beneficial for the small height flexible sheet pile wall. However, in the application of STPW in stiff grounds this minimum embedment depth requirement tends to be over conservative and not economical, and even inconsistent with limit states design concept, especially for the high retaining height and large diameter STP wall. Structural pile failure becomes dominant ultimate limit state over a certain embedment depth (d_e). This can be considered as a critical depth, over which no significant contribution of the d_e increase can be expected for ULS, and this critical depth might be much less than the minimum required embedment depth. The common practice using minimum embedment depth in the simple method should be considered as an option, not requirement and the required performances of the limit states, e.g., SLS and ULS should be examined by reasonable methods, considering the non-linearity of soil – structure interaction.

Combination of elasto-plastic analysis and limit equilibrium method should be a common design practice for the large diameter STPW in stiff ground. However, in the application of the non-linear subgrade reaction method, there are several issues remained for the further research. For examples, modeling of p-y relation, including the evaluation of the parameters used in the p-y curves. The estimation of modulus and strength of soil/rock is key issues for the very stiff ground with very large STP-N values. The variability of ground conditions are also major uncertainties in the design and construction of the wall. Especially as the depth of stiff layer could significantly control deformation as shown in Fig. 6. The data recorded in the press-in process of the pile could contribute to the reduction of the effect of uncertainty and economical and safe construction (Suzuki et al., 2021a and 2021b). To establish the more reliable methods, accumulating field data is of critical importance, as reliable database on site ground conditions, wall specifications, and wall behavior during and after the construction should be the sources for identifying the critical issues and for updating the design method.

As for the earthquake loading, two issues can be pointed out, one is dynamic earth pressure and the other the residual earth pressure after the loading. Even for the large flexural rigidity of the wall with secured fixity by the stiff ground, a relatively large dynamic wall deflection could be generated in the cantilever wall, which might cause the seismic earth pressure different from the one on the rigid wall and increase the residual earth pressure. They are closely related to the wall stress and residual displacement. To have answers on these issues, the further researches should be performed by the physical and numerical studies and field study of the wall after the strong earthquake.

The outcome derived from the TC1 activity will be summarized and reported as a form of final report soon.

5. References

Association of Steel Pile (ASP), 2009. Design Manual of Self-Standing Steel Sheet Pile Wall. (in Japanese).

- He, H., 2018. Gyropress (Rotary Cutting Press-in) method in Disaster Recovery Project (Kagoshima Prefecture, Japan), IPA Newsletter, Vol.3, No.1, pp.11-15.
- Hirata, H. and Matsui, N., 2016. Expanding Applications of the Gyro-press Method, Nippon Steel & Sumitomo Metal Technical Report, No.113, 42-48.
- International Press-in Association (IPA), 2014. A handbook of Steel Tubular Pile Retaining Wall Constructed by Gyropress (Rotary Cutting Press-in) Method.
- International Press-in Association (IPA), 2016. Press-in retaining structures: a handbook (First edition)

International Press-in Association (IPA), 2019. Press-in Piling Case History (Volume 1)

- Ishihama, Y., Fujiwara, K., Takemura, J., and Kunasegaram, V., 2018. Evaluation of Deformation Behavior of Self-Standing Retaining Wall Using Large Diameter Steel Pipe Piles into Hard Ground. Proceedings of 1st International Conference on Press-in Engineering, Kochi, pp. 153-158.
- Ishihama, Y., Takemura, J., and Kunasegaram, V., 2019. Analytical evaluation of deformation behavior of cantilever type retaining wall using large diameter tubular piles into stiff ground, Proceedings of the 4th International Conference on Geotechnics for Sustainable Infrastructure Development, Hanoi, pp. 91-98.
- Japan Road Association (JRA), 1999. Road Earthwork, Guideline for the Construction of Temporary Structures, (in Japanese)
- Kunasegaram, V., Takemura, J., Ishihama, Y., and Ishihara, Y., 2018. Stability of Self-Standing High Stiffness-Steel Pipe Sheet Pile Walls embedded in Soft Rock. Proceedings of 1st International Conference on Press-in Engineering, Kochi, pp.143-152.
- Kunasegaram, V., Shafi, SM, Takemura, J. and Ishihama, Y., 2019. Centrifuge model study on cantilever steel tubular pile wall embedded in soft rock, Proceedings of the 4th International Conference on Geotechnics for Sustainable Infrastructure Development, Hanoi, pp. 1045-1052.
- Kunasegaram, V. and Takemura, J., 2019. Deflection and failure of high stiffness cantilever retaining wall embedded in soft rock. *International Journal of Physical Modelling in Ge-otechnics*, https://doi.org/10.1680/jphmg.19.00008
- Miyanohara, T., Kurosawa, T., Harata, N., Kitamura, K., Suzuki, N., and Kajino, K., 2018. Overview of the Self-standing and High Stiffness Tubular Pile Walls in Japan, Proceedings of the First International Conference on Press-in Engineering, Kochi, pp. 167-174.
- Mochizuki, K., Isobe, K., Takemura, J., and Ishimhama, Y., 2019. Numerical simulation for centrifuge model tests on the stability of self-standing steel pipe pile retaining wall by Rigid Plastic FEM. Proceedings of the 4th International Conference on Geotechnics for Sustainable Infrastructure Development, Hanoi, pp. 481-488.
- Shafi, S, M., Takemura, J., Kunasegaram, V., Ishihama, Y., Toda, K., and Ishihara, Y., 2021. Dynamic behavior of Cantilever Tubular Steel Pile Retaining Wall Socketed in Soft Rock. Proceedings of 2nd International Conference on Press-in Engineering, Kochi (to be published).
- Suzuki, N. and Kimura, Y, 2021. Summary of case histories of retaining wall installed by rotary cutting press-in method, Proceedings of 2nd International Conference on Press-in Engineering, Kochi (to be published).
- Suzuki, N., Nagai, K, and Sanagawa, T., 2021a. Reliability analysis on cantilever retaining walls embedded into stiff ground (Part 1: contribution of major uncertainties in the elasto-plastic subgrade reaction method), Proceedings of 2nd International Conference on Press-in Engineering, Kochi (to be published).
- Suzuki, N., Ishihara, Y. and Nagai, K, T., 2021b. Reliability analysis on cantilever retaining walls embedded into stiff ground (Part 2: construction management with piling data), Proceedings of 2nd International Conference on Press-in Engineering, Kochi (to be published)

Takada, H., 2016. Restoration and Reconstruction of Kyu-Kitakami River, IPA Newsletter, Vol.1, No.1, pp.3-5.