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State of the art report on application of cantilever type steel tubular pile wall embedded to stiff grounds

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ABSTRACT: IPA-TC1 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 state of the art report overviews the research activities done by TC1, i.e. case study, physical modeling, numerical analyses, parametrical study by design models, and gives considerations and remaining challenges for the rational design of this type of wall.

1 INTRODUCTION

1.1 *Motivation*

Various types of earth retaining structures or walls have been employed in the history of civil engineering, such as masonry walls, RC concrete walls, sheet pile wall, mechanically stabilized earth wall. Similar to the other civil engineering structures, these retaining walls should satisfy the required performance under the design conditions. Several conditions should be considered in the selection and design of the retaining structures, such as design loads (actions) and site environment. Among the several options of the earth retaining systems, embedded retaining walls are common one for both temporary and permanent structures and various types of embedded retaining walls are used are used depending on the site conditions (Gaba et al. 2017). Among the embedded retaining walls, cantilever wall is the simplest wall, of which stability is relied on only the embedment soil or rock against the load from the retained side. With the simple retaining mechanism and a relatively large wall deflection, this type of wall has been mostly used for temporary work or for the permanent wall with small height.

However, thanks to the innovative pile installation method, like rotary cutting press-in method (e.g. Gyropress), the applicability of steel tubular pile wall (STPW) has increased significantly for various structures (road, harbor, railway) and objectives, not only ordinary retaining structures (Miyanohara et al. 2018, Suzuki & Kimura 2021), but also restoration, rehabilitation and reconstruction of disaster areas (Takada 2016, He 2018). The installation abilities of large steel tubular pile (STP) into very stiff grounds with low noise and vibration and without damage of pile end are all critical advantages of the rotary cutting press-in method (Table 1). The damage of pile is a main concern in the pile penetration in stiff layer (Randolph 2021). Figure 1 shows a typical example of STPW application for road widening project using a narrow steep slope reinforced by ground anchors with several requirements from road traffic and residential sides (Kitamura & Kitamura 2019).

The combination of large diameter and high rigidity STP, and the stiff embedment ground enables the application of the cantilever embedded walls with large retained height (Figure 2). Figure 3 shows the relationship between the calculated wall deflection and wall retained height for two ground conditions (relatively dense sand with SPT N-value=50 and soft rock with unconfined compression strength q_u = 1.5MPa). The calculations were made assuming the ordinary static load based on Cantilever Steel Sheet Piles Retaining Wall - Design Manual (JTASP-PACTC 2007) with the conditions shown in Figure 4. In Figure 3, allowable displacements of requirement 1 are also shown on the stability of embedment soil (δ_{gs}) and serviceability of the facility on the retained soil (δ_T). From the calculated results, it can be confirmed that by the combination of large diameter STP and stiff embedment ground, 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, JTASPPACTC 2007). Therefore, simple application of the current design method to the cantilever type STPW embedded in stiff grounds may require

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Table 1. Advantages and concerns of rotary press-in cantilever large diameter steel tubular pile wall.

Advantages
- Applicability to severe construction site environment, such as small working space, steep slope, hard ground, noise- vibration restriction, remote operation at the failure risk slope; - Construction accuracy and safety; - No traffic interruption, short construction time; - Continuous recording of pile installation process.
Concerns
- Technology advanced without rational design method and currently adopted design methods not considering the specific features of the wall, namely, very large stiffness piles in stiff ground; - Few records on the critical performance of the wall; - Relatively expensive compared to the other common retaining walls; beside the facility cost, material, welding and transportation could be reduced by the rational design and construction practice.

Figure 1. Application of STPW (H=7.7-12.4m, l_p =20.5-24.0m) for road widening projects (Kitamura & Kitamura 2019).

excessive embedment depth, or increase a risk of failure caused by the unexpected performance of the wall.

Several concerns can be pointed out in the commonly used current design methods, such as,

1) The minimum embedment depth (d_0) requirement using characteristic value (β), such as $d_0 \geqq 3/\beta$ (Figure 4) should be verified, as it is based on long flexible wall behavior in an infinite uniform elastic media, which conflicts the rigid nature of large diameter steel tubular piles;
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, which is not considered 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.

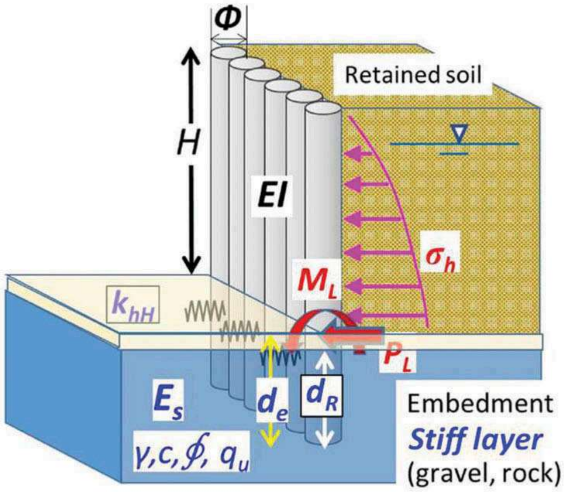


Figure 2. Cantilever STPW embedded in stiff ground and conditions used in the design.

1.2 *Objectives of TC1*

To answer the above-mentioned concerns and establish a rational design procedure, Technical Committee TC1 "Application of Cantilever Type Steel Tubular Pile Wall embedded to Stiff Grounds" was set up in IPA. Four working groups were created in TC1 with several tasks as shown below. Some findings related to the task were presented in the report.

1.2.1 *Tasks of Working Group*

WG1 on design method:

- Task 1: to investigate design methods presently used, 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 new rational design method of large diameter tubular steel pipe wall including seismic design.

WG2 on centrifuge model test:

- Task 1: to clarify mechanical behavior of large diameter tubular steel pipe wall subjected to static load in stiff ground.
- Task 2: to analyze influence of critical conditions such as embedment depth, ground stiffness and strength on the behavior of wall.

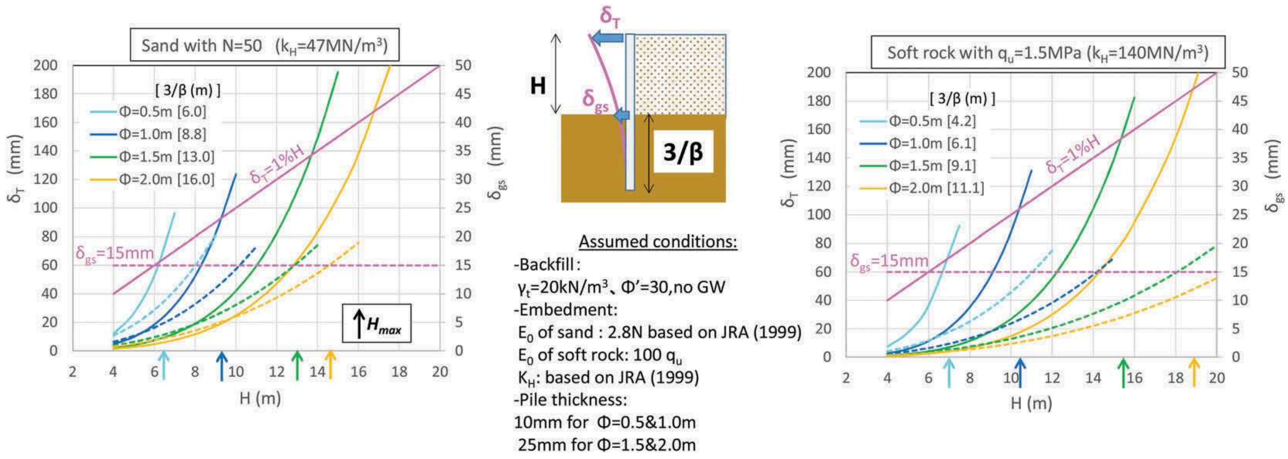


Figure 3. Wall displacement estimated simplified method (JTASPPACTC 2007; IPA 2014 & 2021).

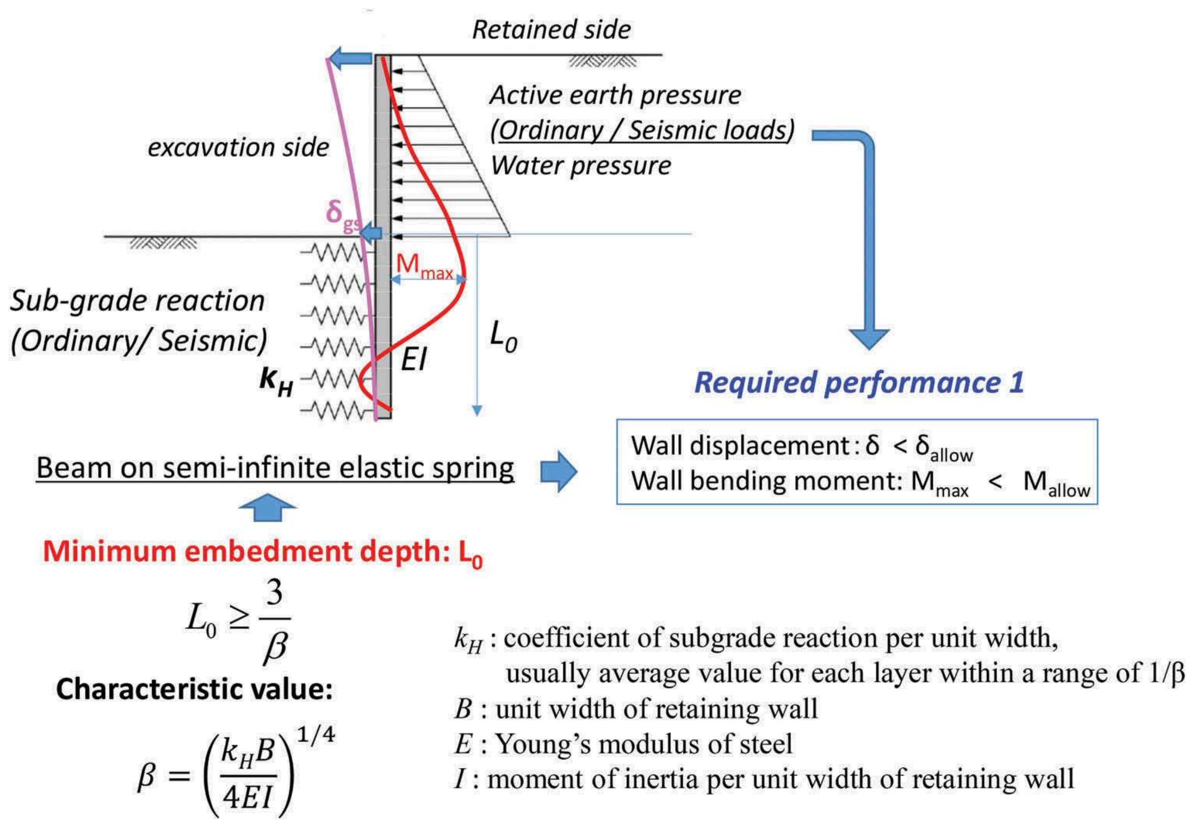


Figure 4. Simplified method, static verification method with a linear elastic subgrade reaction (beam on elastic base) model, which is commonly used performance verification for permanent and variable situations (ordinary static/seismic load), (JTASPPACTC 2007; IPA 2014 & 2021).

- 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 against earthquake load.

WG3 on numerical analyses:

- Task 1: to verify and calibrate 3D FEM method by centrifuge modeling.
- Task 2: to analyze the 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 much 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 STUDIES

Number of applications of the rotary press-in method is shown in Figure 5. 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). Figure 6 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 1.0m have been used more than 30% with 2.0m maximum. The project shown in Figure 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 gravel 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 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 ($d_o \geqq 3/\beta$) were adopted especially for the road construction projects. Although the number of applications has increased significantly, very limited records

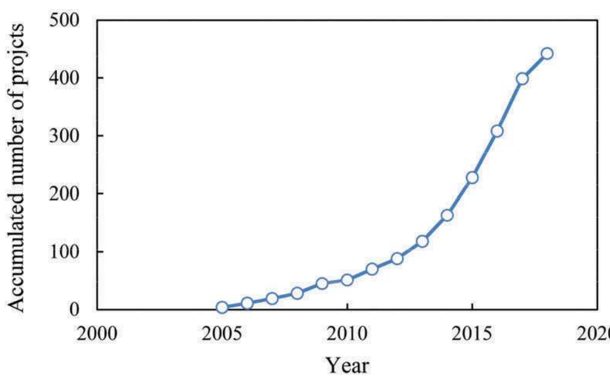


Figure 5. Accumulated number of the application of the rotary press-in method (Suzuki & Kimura 2021).

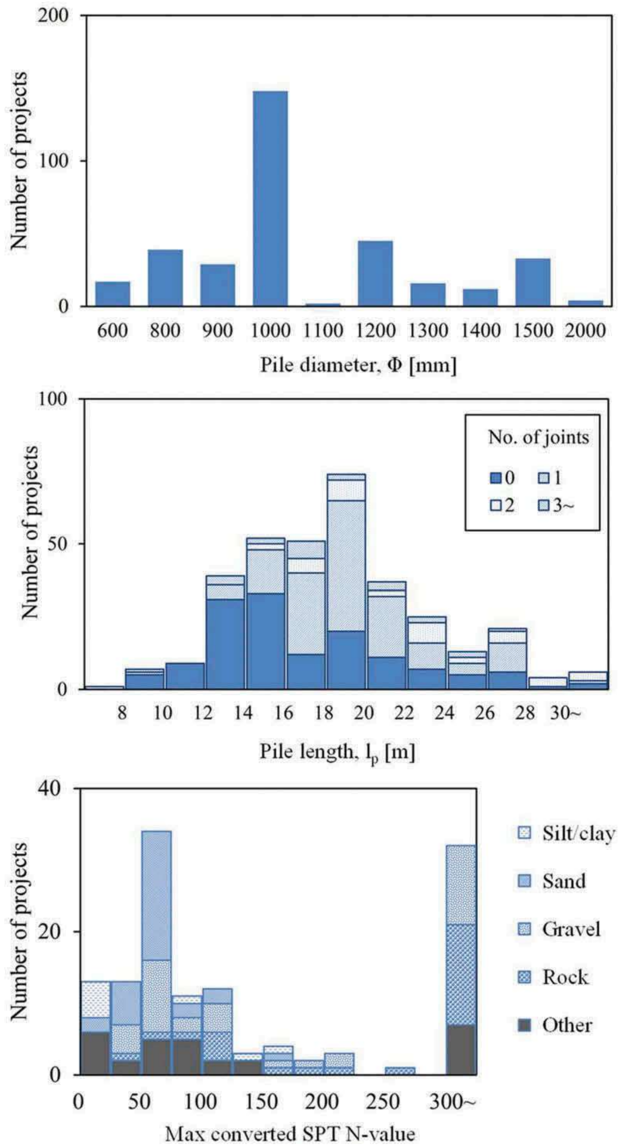


Figure 6. Summary of case records of STPW installed by rotary cutting press-in method (Suzuki & Kimura 2021).

are 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 (ULS), and the wall performance from SLS and ULS under various actions, e.g. static and seismic loadings with detailed site conditions are critically important to rationalize the design procedure.

Case studies of foundation in stiff grounds, e.g. soft rocks, with detail field measurements are rather limited, which are mostly on the end bearing capacity of piles. Nanazawa et al. (2015) conducted an intensive study on the end bearing capacities of piles installed in rock ground, which covering various codes and design methods, analyses of field loading tests on 94 sites. At the most of the sites only standard penetration test were conducted and due to the capacity limitation of the machine, the majority of piles were installed in the rock ground of equivalent N-values less than 200. Beside N-values, the other ground properties are limited, such as unconfined compression (UCC) test data available for 10% of the cases, and very few on the rock quality (RQD, classification). As for the driven steel pile into soft rock, several researches have been done. Randolph (2019) delivered a keynote lecture on various aspects of the design of piles embedded in soft rock, covering rock properties of pile design, the effect of construction methods and techniques for optimising pile performance, axial load transfer parameters, effects of strain softening and cyclic loading, and analysis approaches for laterally loaded piles in rock. On the contrary to the piles driven or socked in the soft rock, very limited researches have been made for the retaining wall embedded in rocks, especially field tests, including the monitoring of actual structures.

3 BEHAVIOR OF LARGE DIAMETER STPWS IN STIFF GROUND AND CRITICAL CONDITIONS

Over the past decades, extensive investigations based on the physical modelling of excavations on a cantilever and propped walls embedded in clays and sandy soils have contributed to the development of design codes and the calibration of numerical models (Padfield & Mair 1984, Bolton & Powrie 1987 & 1988, Richards & Powrie 1998, Day 1999). Also, the observations from numerous case histories (Long 2001, Ou et al. 1993) related to the real field applications in a vast range of soil conditions and the failure of earth retaining structures (D'Andrea & Day 1998, Whittle & Davies 2006) oftentimes revised the codes for the safe and economic design of retaining structures in sand and clays. However, the available literatures based on physical models or the real field experiments to illustrate the behaviour of self-standing walls embedded in soft rocks are extremely rare (e.g. Richards et al. 2004). Perhaps it might be attributed to the difficulties in the installation and creating the failure of such large retaining structures in the real field or even in centrifuge models with required dimensions.

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.

3.1 *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, 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 embedment 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 de is the sum of the top layer depth and d_r (Figure 2). To generalize the embedment or socket depth, normalized embedment depth ($d_e\beta$ or $d_R\beta$) were estimated. The d_e and d_R adopted in the centrifuge tests were all far below the minimum embedment depth ($d_o = 3/\beta$).

3.1.1 *Series I model: 2D retaining wall*

Model test setup developed for this series is shown in Figure 7. This setup can model the high stiffness embedded cantilever wall behavior with large retaining height from the serviceability limit state (SLS) to the ultimate limit state (ULS) in a geotechnical centrifuge. The former performance corresponding an excavation process (ordinary loading) can be simulated by draining the water from the closed rubber box placed in front of the wall and the latter extreme loading process is created by feeding the drained water to backfill sand contained in a rubber box behind the wall. For the model which did not exhibit large displacement after rising the water level, the centrifugal acceleration was increased stepwise with a 5g increment up to 95g to observe the large movement of the wall. In this series, several centrifuge model tests were conducted in plane strain (2D) condition using aluminum plate walls with per width flexural rigidity (EI) equivalent to STPW with $\Phi = 2.5$ m & t = 25 mm and 1.0 m & t = 10 mm in a prototype scale under 50g centrifugal acceleration. Artificial soft rocks and sand were used as wall embedment media (Kunasegaram et al. 2018, Kunasegaram & Takemura 2019).

Observed wall top displacements and rotations of 12m high rigid walls $(\Phi_{eq} = 2.5\,\text{m})$ with d_e = 2.5 m

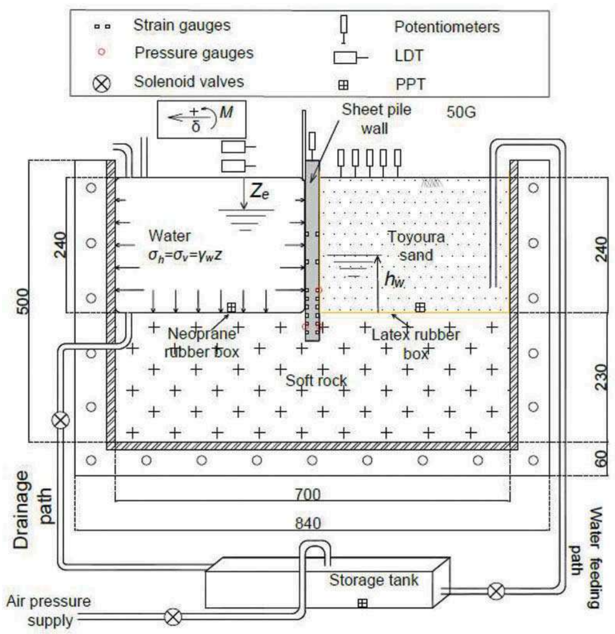


Figure 7. Centrifuge model test setup on rigid plate wall: Series I (Kunasegaram & Takemura 2019).

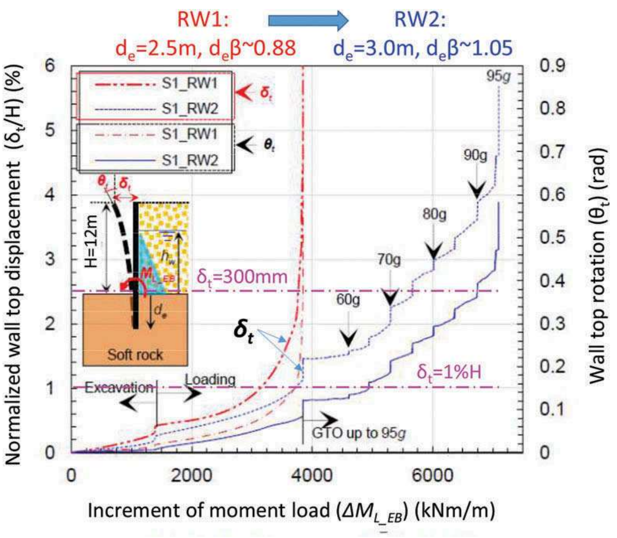


Figure 8. Effect of embedment depth observed in Series I centrifuge tests (Kunasegaram & Takemura 2019).

($d_e\beta = 0.86$) and 3.0 m ($d_e\beta = 1.05$) are compared in Figure 8. As a unified loading index in the two processes, the moment load applied at the excavation bottom is used in the horizontal axis. Though the $d_e\beta$s of the model wall 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= 120mm, 1.0% wall height (H)). Taking wall top displacement δ_t = 300mm, which is an allowable displacement as required performance 2 against level 2 earthquake (JTASPPACTC 2007), as a reference of ULS, the safety margin at SLS to the requirement failure are about 25% (from 3100 to 4000 kNm/m) for d_e = 2.5m and about 40% (from 4000 to 5650 kNm/m) for d_e = 3.0m respectively. These margins seem not large enough, but it should be pointed out that these required performances are introduced for small retained height, e.g. H < 4 m. Though the margins for the two embedment depths might not be so different, there is a significant difference in the behaviour over δ_t = 300mm.

As pointed by Li and Lehane (2010), creep has critical effects on the behaviour of embedded cantilever wall. In the centrifuge model the relatively large creep displacements, the disp. increment without load increment, were observed as shown in Figure 8. However, all creep displacements were decreasing with time, except of d_e = 2.5m wall after the final loading. Clear failure took place without additional increment of the load for d_e = 2.5m, while the wall with d_e = 3.0m resisted the additional load more than 7000 kNm/m. The significantly increase of the wall stability by a half meter increment of the embedment for this case can be also confirmed from the deformation and failure observed after the tests as shown in Figure 9. Backward slip failure was confirmed for the wall with d_e = 2.5m wall, but for

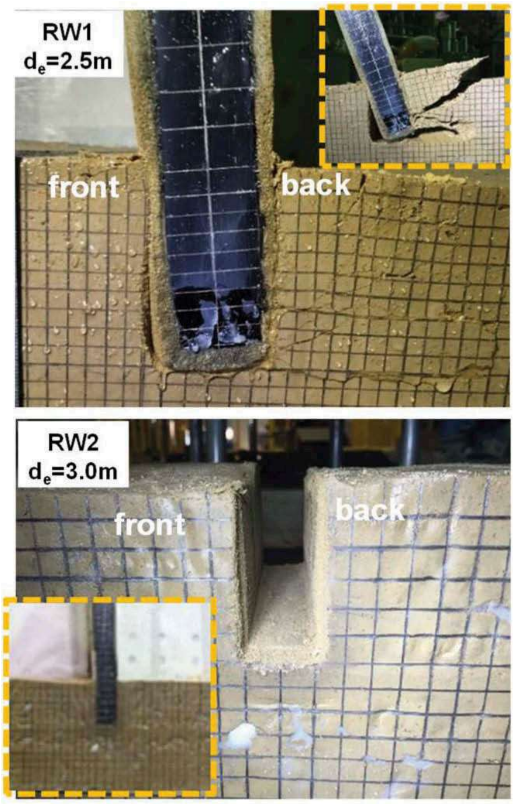


Figure 9. Observed deformation and failure of the cantilever walls (Kunasegaram & Takemura 2019).

d_e = 3.0m, the embedment portion was securely fixed by the soft rock, preventing the catastrophic failure.

3.1.2 *Series II model: Parametric study on rock sock depth and ground conditions*

To investigate the effect of embedment depth (d_e) under clear loading conditions, lateral resistances of the tubular steel pipe wall socketed into soft rock were investigated by centrifuge model tests in 50g centrifugal acceleration. They are two simplified models from the targeted structures and conditions, namely wall model and single pile model, as shown in Figure 10. Two types of model ground were prepared for the two models, single layer of soft rock, and soft rock with overlying sand. Lateral loading tests were performed for $\Phi = 2$m single STP (SP) and STP wall (RPW) made socketed in the two model grounds with different wall/pile embedment depth, d_e, or rock socket depth, d_R (Figure 11). Considering the loading conditions and the displacement behavior of the embedded cantilever wall (Figure 10a), lateral load, P_L, were imposed to pile/wall top by one-way alternate manner as depicted in Figure 12. The load – displacement curves are compared in Figure 13. 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 $[d_R, d_R\beta]$ are shown in Figure 11. From Series II tests, several findings are derived.

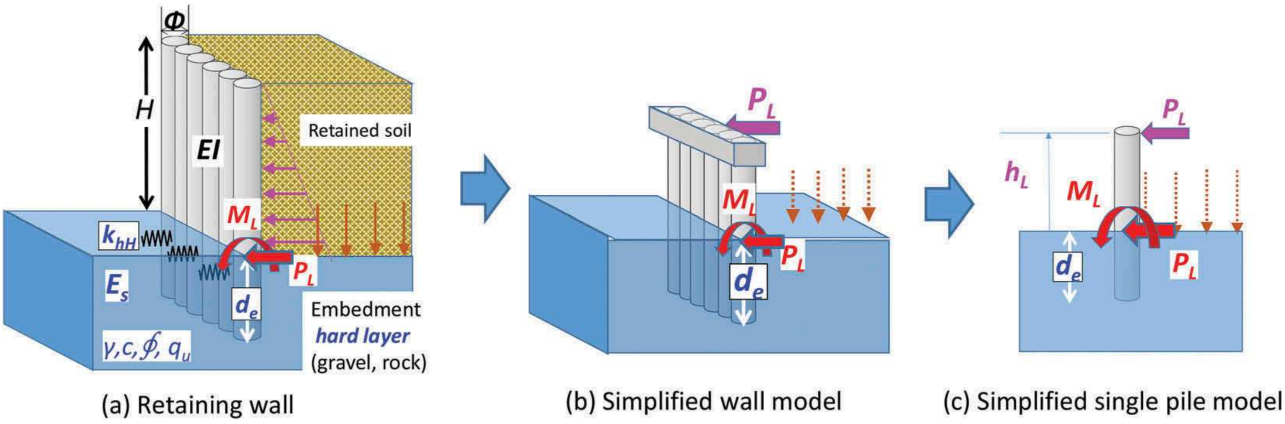


Figure 10. Target structure and simplified models (Kunasegaram et al. 2019).

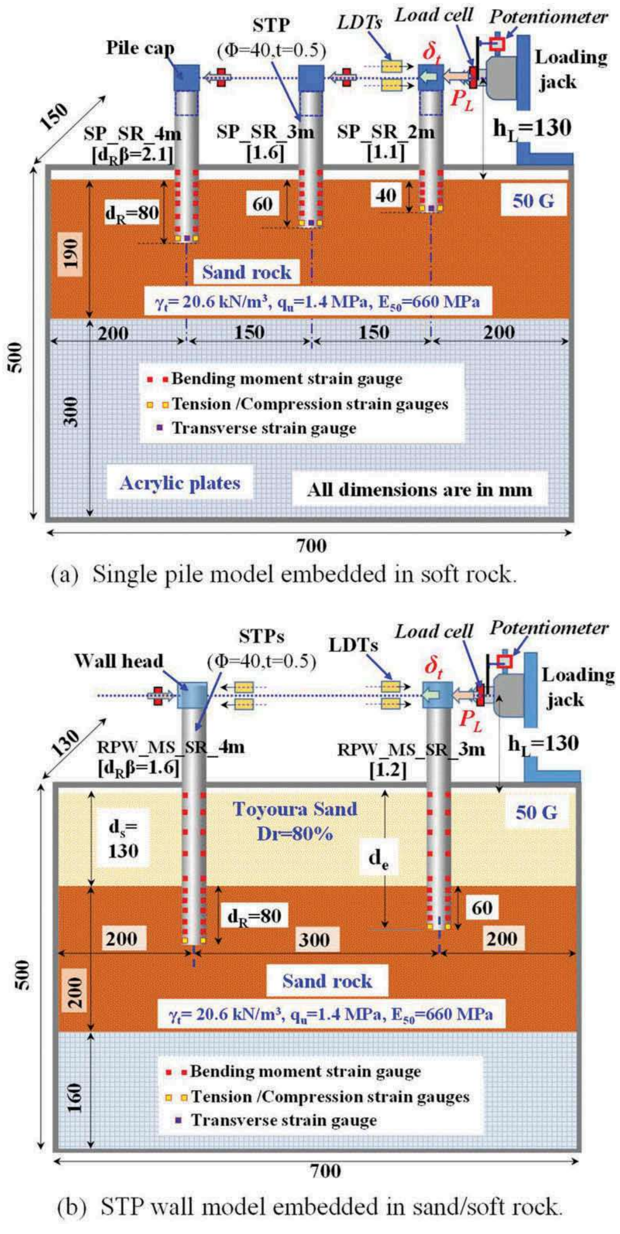


Figure 11. Centrifuge model test setups for Series II (Kunasegaram et al. 2019).

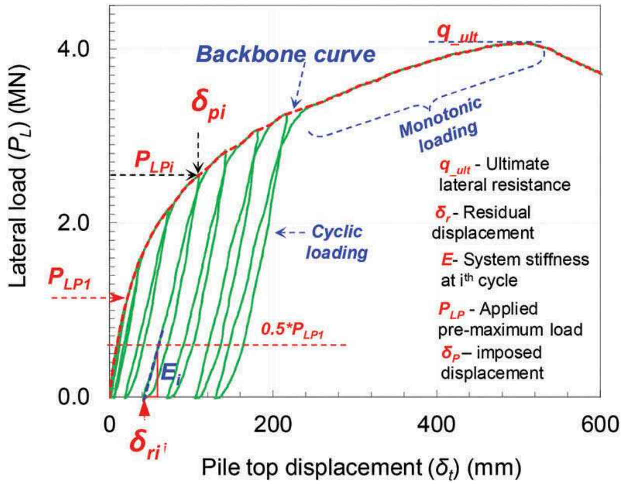


Figure 12. Typical load - displacement curves, and definitions of load and displacement parameters (Kunasegaram et al. 2019).

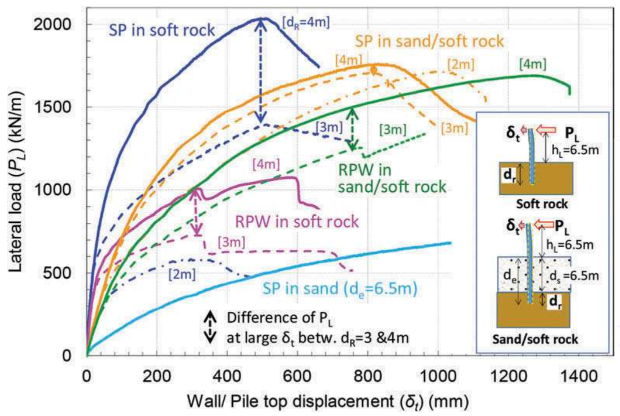
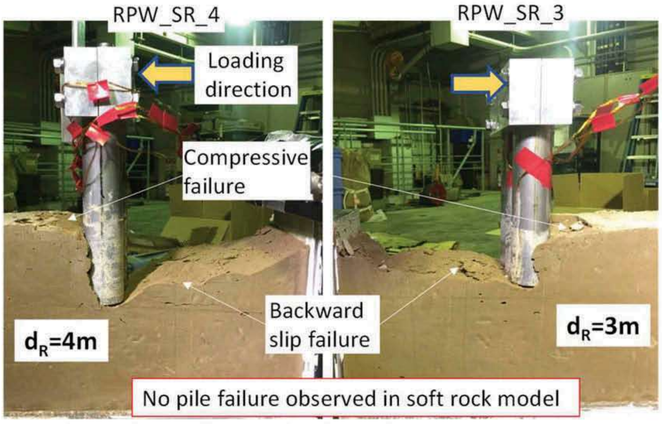
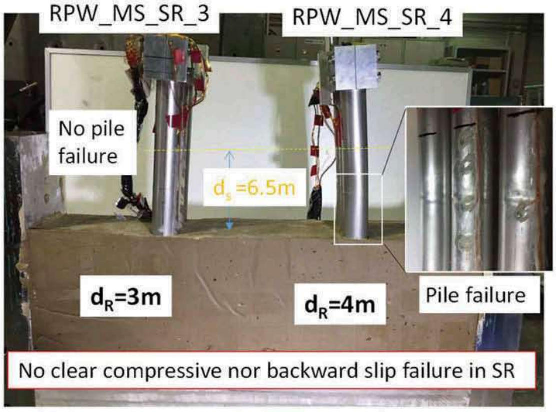


Figure 13. Observed deformation and failure of the cantilever walls (Kunasegaram et al. 2019).



(a) STP wall embedded in soft rock.



(b) STP wall embedded in sand/soft rock.

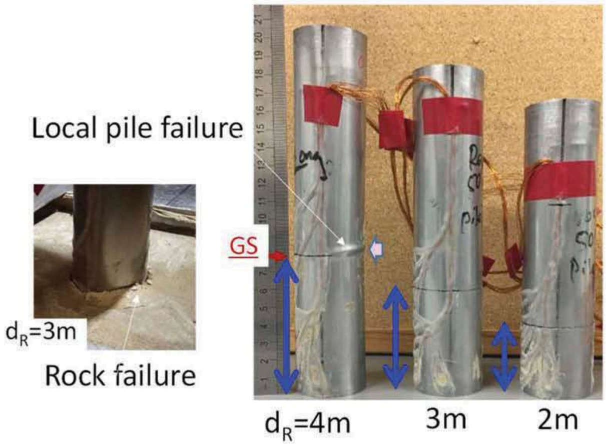
Figure 14. Observed failures of the STP wall model (Kunasegaram et al. 2019).

1) Lateral resistances of wall and single pile increase with d_R, but the trend of the increase depends on imposed displacement and, ground condition (Figure 13).
2) The observed failures of soft and pile/walls are shown for STP wall models and single pile models in Figures 14 & 15 respectively. These failures are controlled by d_R and d_e and the ground types.
3) Optimum socket depth, over which the effect of d_R is insignificant, is much smaller than 3/β. As shallow rock part mainly resists 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 sub-grade reaction and the ultimate resistance.
5) The effects of socket depth and the difference between the pile and the wall on the lateral resistance (Figure 13) and the residual displacement after loading (Figure 16) 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 (Figures 17 & 18).

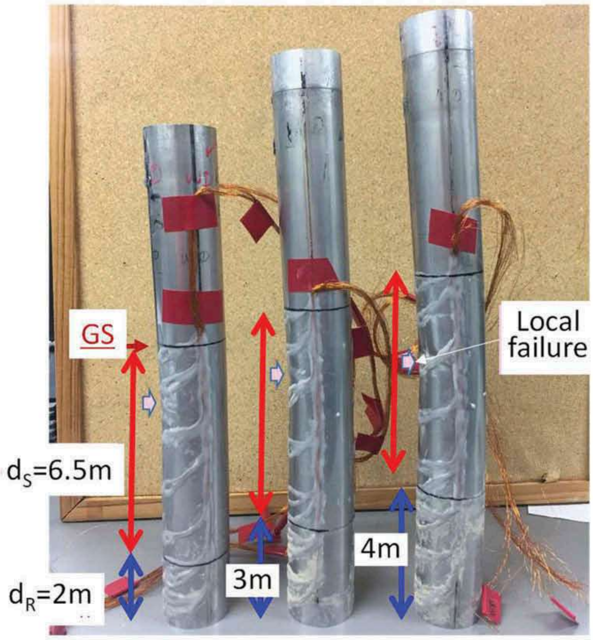
The above findings are all critically concerned to the issues for the rational design procedures, such as, critical embedment depth, non-linearity of p-y curves, and accumulation of residual displacement of the wall subjected to various loading history.

3.1.3 *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



(a) Single piles embedded in soft rock.



(b) Single piles embedded in sand/soft rock.

Figure 15. Observed failure of STP (Kunasegaram et al. 2019).

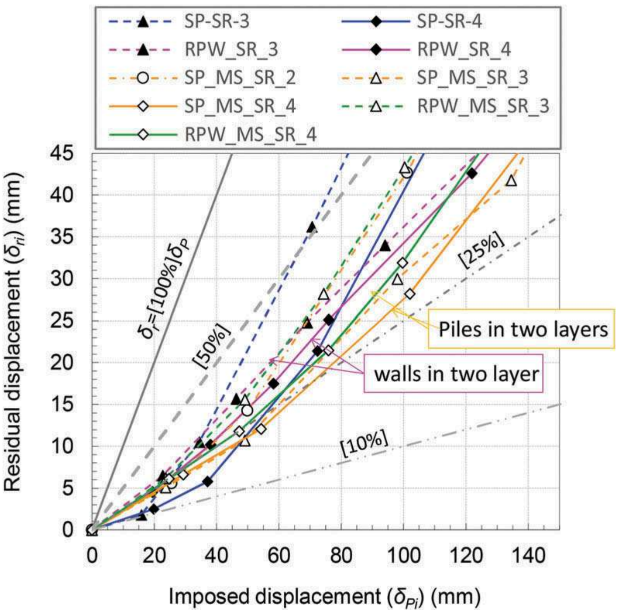


Figure 16. Residual displacement against imposed displacement (Kunasegaram et al. 2019).

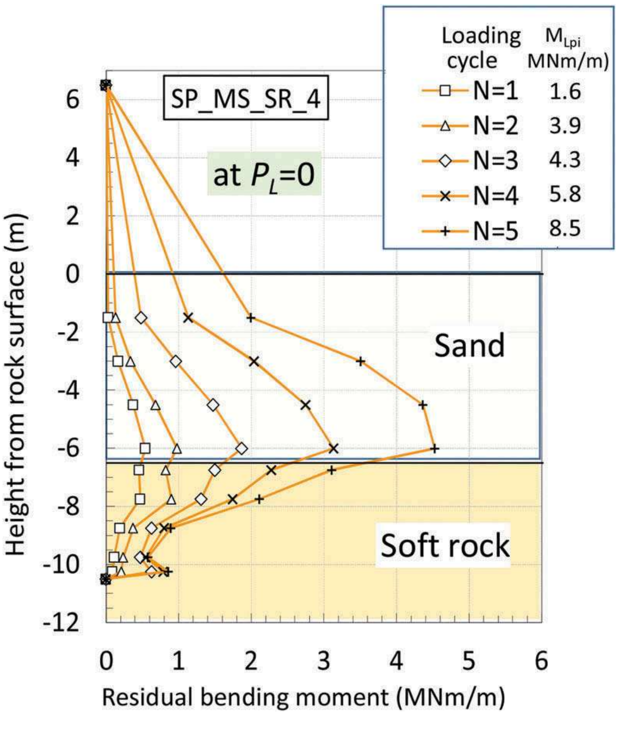


Figure 17. Residual bending moment of the STP wall embedded in sand/rock (Kunasegaram et al. 2019).

model in Series I, were made using the same STP wall in Series II as illustrated in Figure 19. Several dynamic loadings were applied by sinusoidal input acceleration to the models with different embedment depths of d_R = 2.5 m and 3.0 m (Shafi et al. 2021). In the loading sequence, water was fed in the backfill to rise the water level (Figure 20). Typical observed wall top displacement and earth pressured behind the wall are

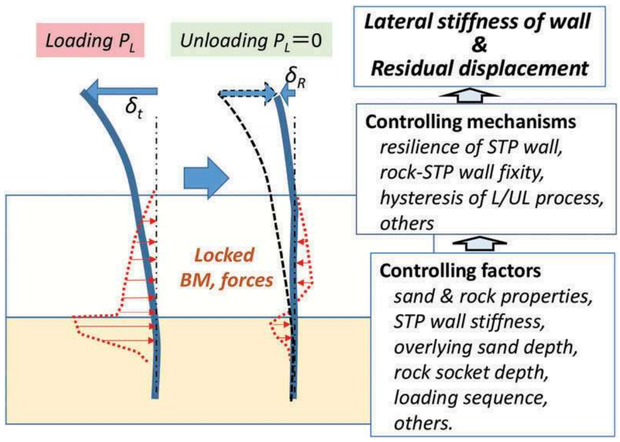


Figure 18. Hypothetical mechanism of residual displacement after unloading and lateral subgrade reaction in reloading (Kunasegaram et al. 2019).

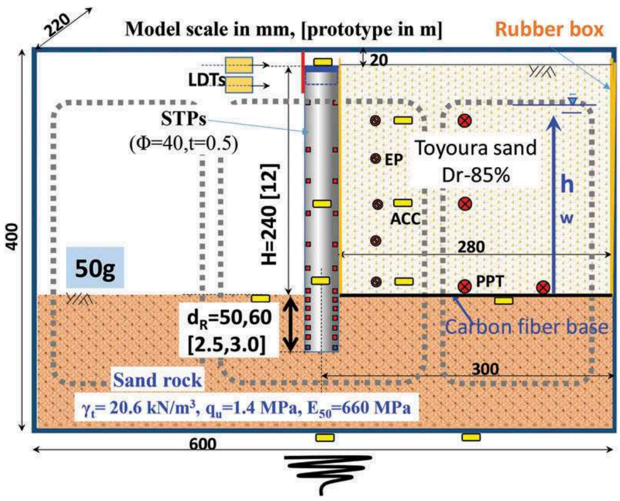


Figure 19. Centrifuge model test setup of STP wall for dynamic loading: Series I (Shafi et al. 2019).

shown in Figure 21. In the early stage of cyclic loading, the amplitudes from the trends and the residual wall displacement are relatively large compared to the later stage of loading where steady cyclic behavior is observed for the all measurements. This typical behavior could be confirmed for the wall with d_R = 3.0 m ($d_R\beta$ = 1.2), but it is the case only for dry shaking for the wall with d_R=2.5m ($d_R\beta$ = 10) as shown in Figure 20. The accumulated wall displacements observed in the entire loading processes were plotted against the cumulative Arias intensity for the walls with d_R = 2.5m and 3.0 m in Figure 22. 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 (Figure 23). This pressure should be considered as an action to

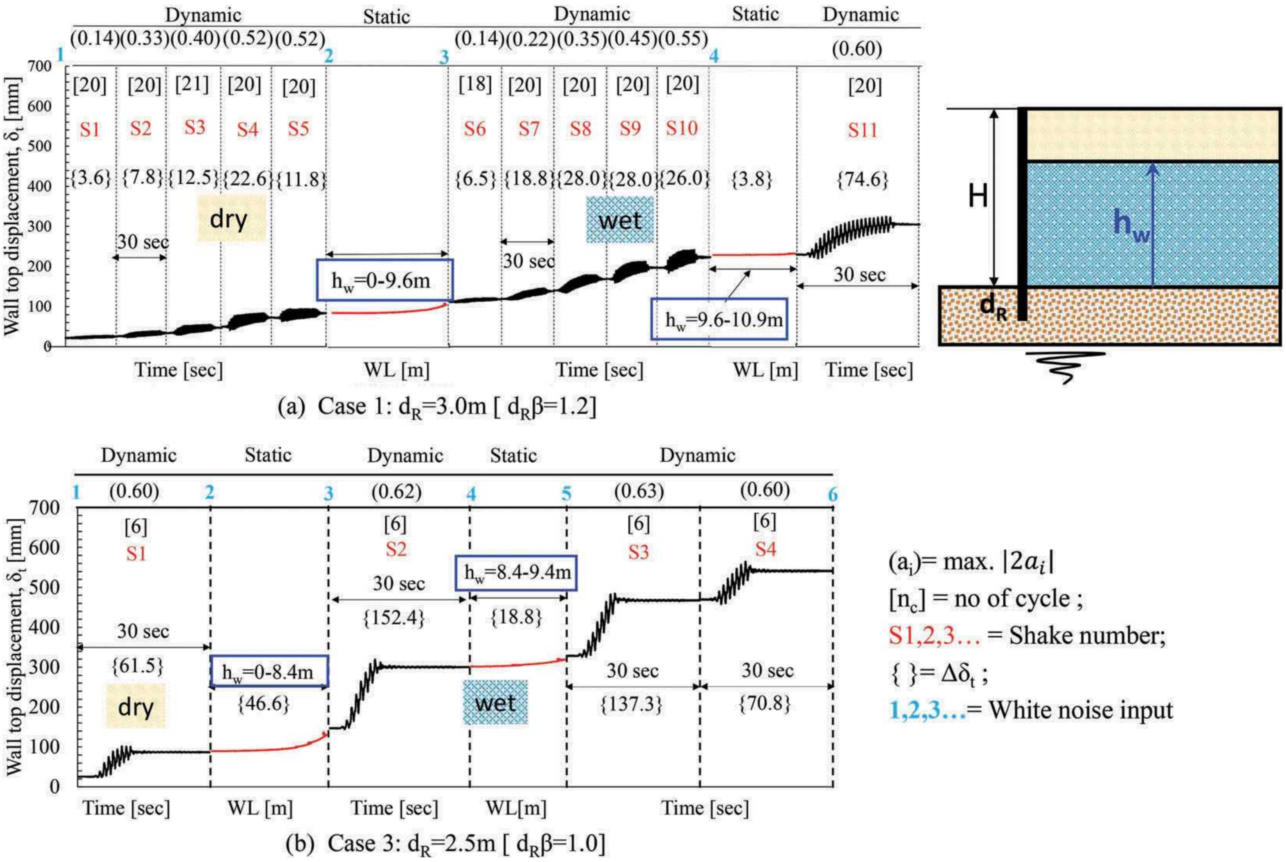


Figure 20. Dynamic and static loading conditions and observed wall top displacement (Shafi et al. 2019).

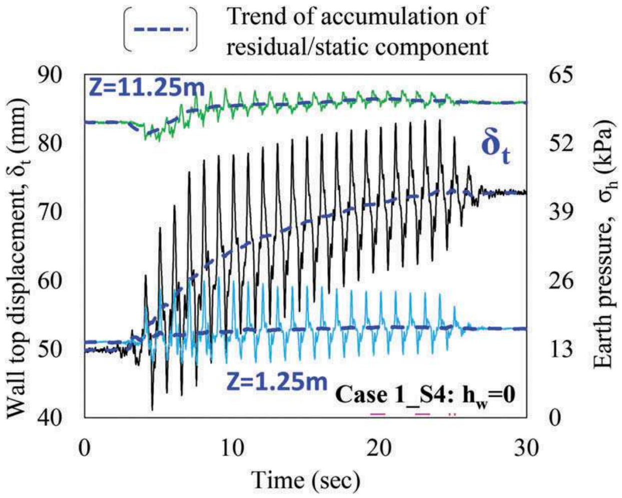


Figure 21. Observed wall top displacement and earth pressure during shaking (Shafi et al. 2021).

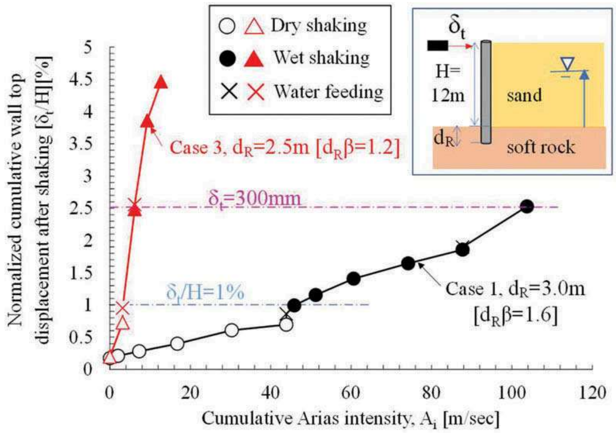


Figure 22. Effect of embedment depth under dynamic loading Series III centrifuge tests (Shafi et al. 2021).

examine the structural safety of the pile and the wall residual displacement after the earthquake. It should be not that no clear ground failure, as observed in Series II (Figure 14), was observed for the wall with d_R = 3.0 m, which had been loaded under very critical conditions (high water table and large intensity of dynamic loading) and d_R = 2.5 m, which was displaced nearly 5% of wall height at wall top (Figure 24). The vertical overburden stress on the rock surface behind the all could prevent the backward slip failure.

3.2 *Numerical studies: Issues remained*

Though the centrifuge model tests could provide valuable results on the mechanical behavior of the cantilever 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,

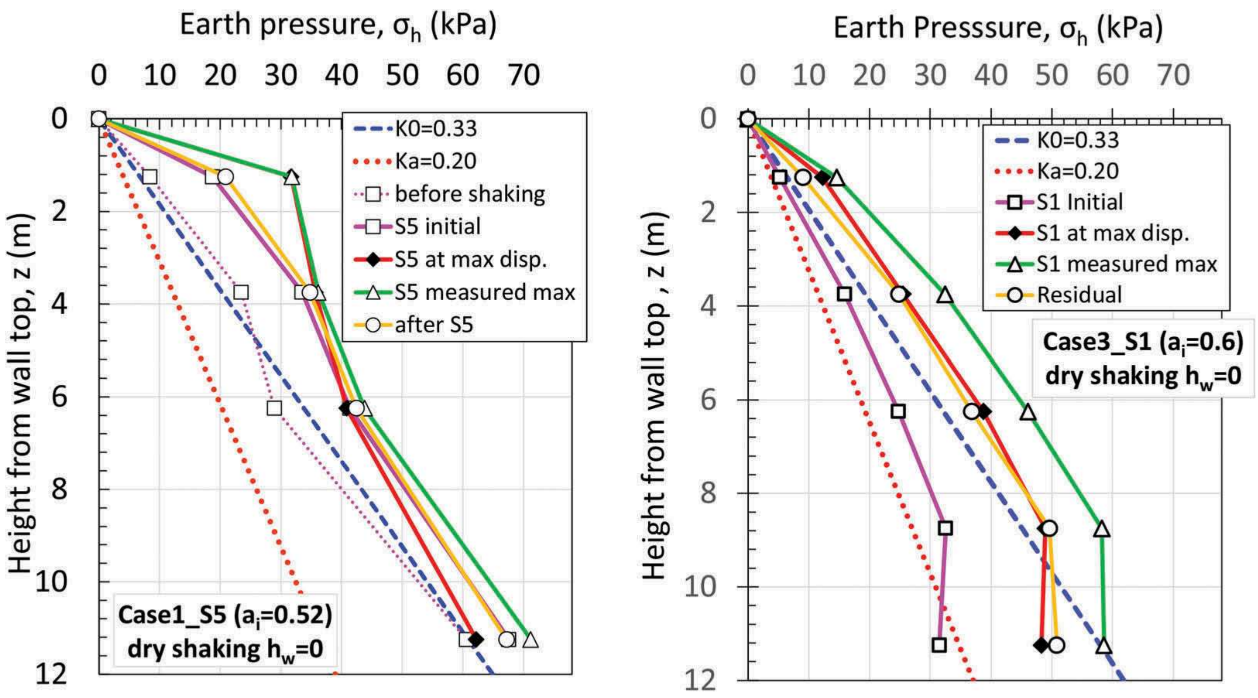


Figure 23. Change of earth pressure distribution on the wall (Shafi et al. 2021).

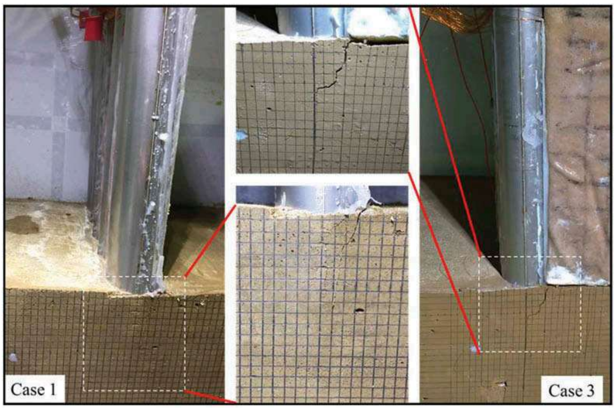


Figure 24. STP wall and embedded soft rock after dynamic loading: Series III centrifuge tests (Shafi et al. 2021).

- 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 (Figures 14 & 15) could be a common ULS for the wall relatively large d_e, even $d_e\beta$ are well below the minimum requirement ($d_e\beta > 3.0$). 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

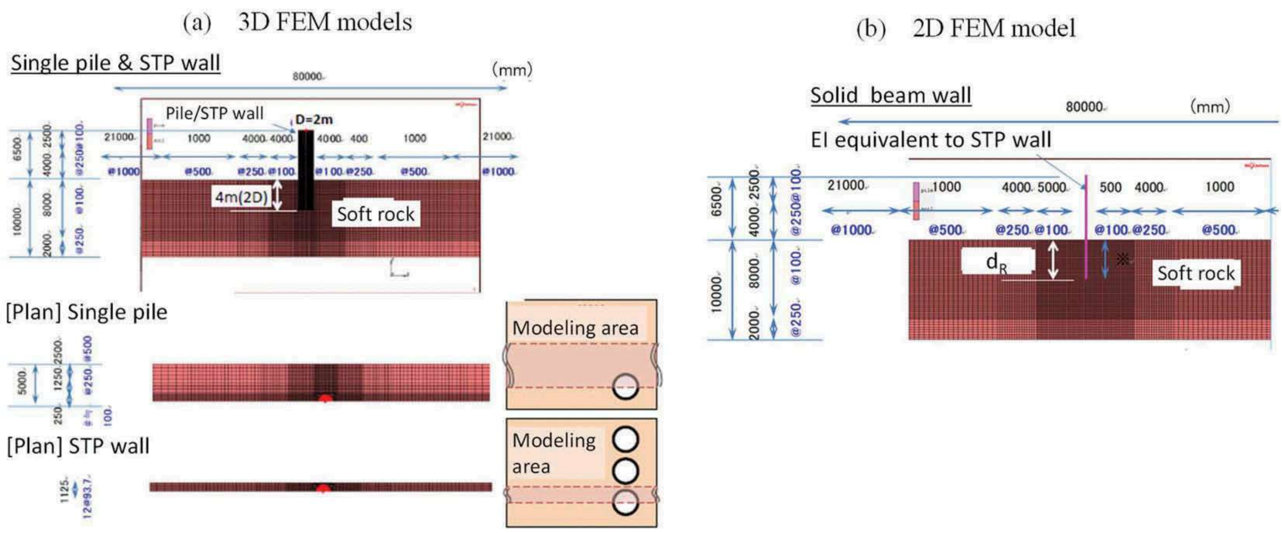
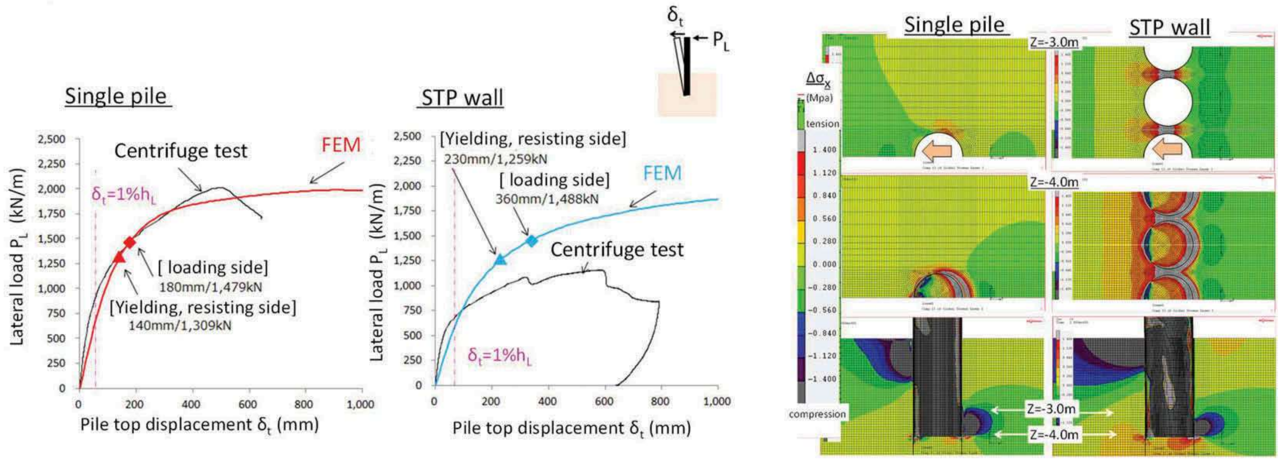


Figure 25. (a) 3D FEM models of single STP and STP wall (Centrifuge test Series II) and (b) 2D FEM model solid beam wall with EI equivalent to that of the STP wall.



(a) Load - displacements

(b) Contours of $\Delta\sigma_h$ at δ_t=200mm

Figure 26. Results of 3D FEM analyses of single STP and STP wall (Centrifuge test Series II) (a) load – displacement with centrifuge test results, and (b) contours of horizontal stress increment.

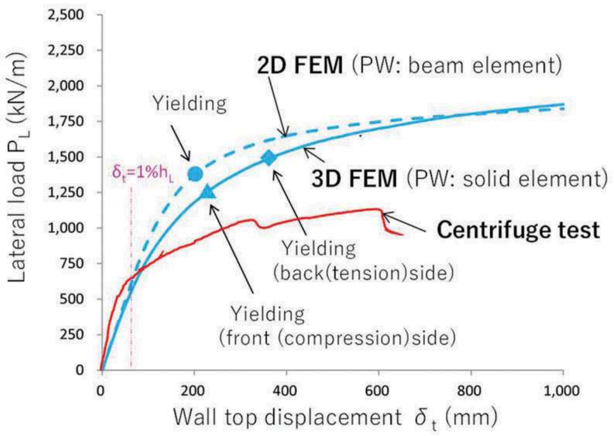


Figure 27. Comparison of 3D and 2D FEM of STP wall embedded in soft rock (d_R=4.0m, Centrifuge test Series II).

with d_R = 4.0 m (Centrifuge test Series II), of which models are given in Figure 25. 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 obtained by the 3D analyses (Single pile and STP wall models) were compared with the centrifuge test result in Figure 26. For the small displacement the FEM could well capture the load – displacement behavior especially for the single pile. The under-estimation of the resistance at the small displacement could be attributed to the relatively smaller rock stiffness used in FEM than the actual soft rock material. The over-estimation of STP wall at large displacement is the limitation of the FEM used in strain localization including the slip type backward failure of the wall (Figure 14).

In Figure 27 the P_L- δ_t curves of STP wall predicted by 3D and 2D models (Figures 25a & 25b respectively) are compared. 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 (Figure 26b). As mentioned above, the analyses overestimate the ultimate resistance, however, from Figure 27 it can be said that the 2D model can be applied without specific consideration of 3D effects of STP wall for the displacement prediction till the SLS.

4 ANALYTICAL STUDIES: SUBGRADE REACTION (P-Y) METHOD

The top wall displacements analyzed by subgrade reaction method using bi-linear p-y relation are plotted against to the relative embedment depth to the minimum requirement ($d_e\beta/3$) in Figure 28. This is the common analytical model for the design of retaining wall called “elasto-plastic analysis” in Japan (e.g. 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, assuming an ordinal loading condition of h_w = 0 m. 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&2021).

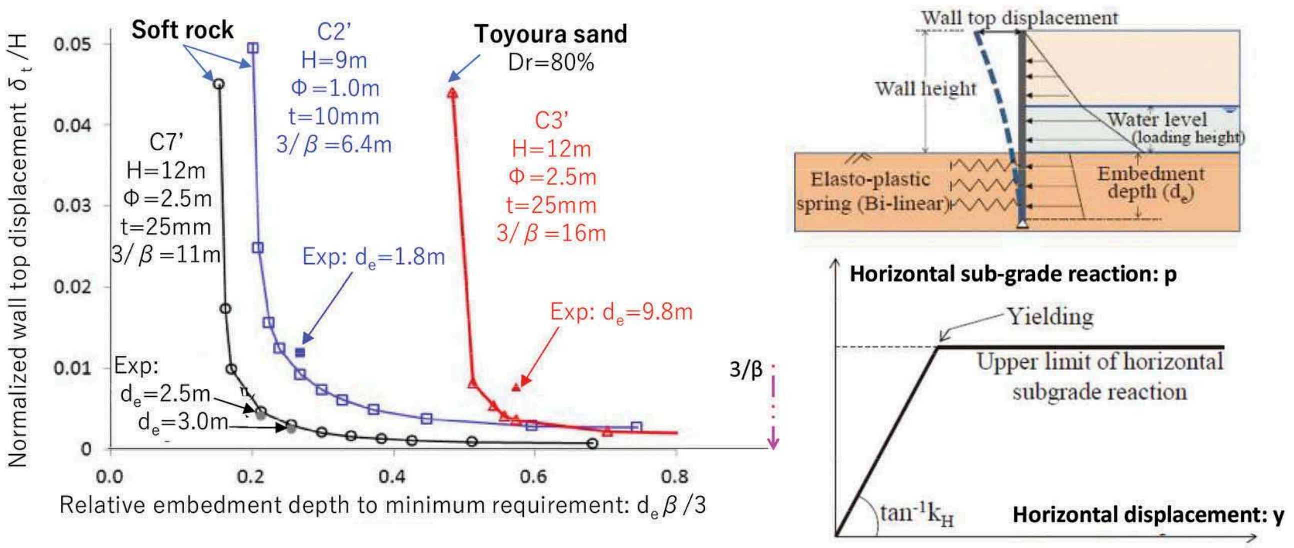


Figure 28. Relationship between wall top displacement and relative embedment depth to the minimum requirement ($d_e\beta/3$) calculated by subgrade reaction method using bi-linear p-y curves for the conditions of the walls in Series I centrifuge model at the end of excavation process, h_w=0m (Ishihama et al. 2019).

Developments of plastic region in the embedment against the water rise, h_w, obtained by the elasto-plastic analysis are depicted in Figure 29. The “plastic” corresponds to the subgrade reaction reaching to the upper limit as showing in Figure 28.

Detailed discussion about the design method for the embedment length of STP wall pressed-in stiff ground was made by Sanagawa (2021).

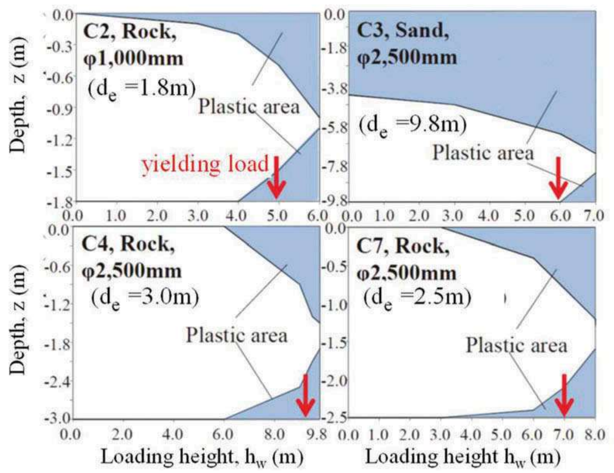


Figure 29. Development of plastic region in the embedded depth with the loading by increasing the water level in the backfill: Series I centrifuge model (Ishihama et al. 2019).

5 CONCLUDING REMARKS: CONSIDERATION OF RATIONAL DESIGN

Current design practice for the embedded cantilever wall using the minimum embedment depth ($d_o = 3/\beta$) adopted in the simple design method (JTASPPACTC 2007, IPA 2014&2021) 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 (API 2002, Liang et al. 2009, Reese 1997). As its simplicity, this simple method could be beneficial for the small height flexible sheet pile wall. However, in the application of STP wall 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 STP wall 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 SPT-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 Figure 13. 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&b). 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 (see Figures 17&18,Figure 24). 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.

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