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Development of Piled Geo-wall (A new type reinforced soil wall)

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ABSTRACT: This study aims to achieve a new type of independent reinforced soil wall (Piled Geo-wall) that can be substitute for one made up of concrete with similar scale, and to contribute to sustainable development. In order to confirm the practicability of the novel structure, three experimental studies with static and impact loading tests and a dynamic centrifuge model test were carried out in the past years. Simple design methods of the novel structure, which can reproduce the results of the experiments, are introduced in this paper.

Keywords: Reinforced Soil Wall, Pile Foundation, Earth-Retaining Wall and Rock-Fall Protection Structure

1. INTRODUCTION

The high ductility of soil structure reinforced by geogrid is well known, as is the possibility of building independent soil wall. The independent reinforced soil wall has been applied to such diverse structures as rock-fall protection walls, mud and snow avalanche protection walls and the suchlike. Since it can be built using existing soil at the construction site if it is compactable one, they are being used ever more frequently as one of economic and CO2 reducible structures. At present, however, the adoption of the spread foundation for the independent reinforced soil wall makes the design too wide for application to narrow construction sites, such as beside mountainous road. If a narrow independent reinforced soil wall as like as RC wall with pile foundation is achieved, it could be widely applied. And it can also be substitute for concrete ones and contribute sustainable development.

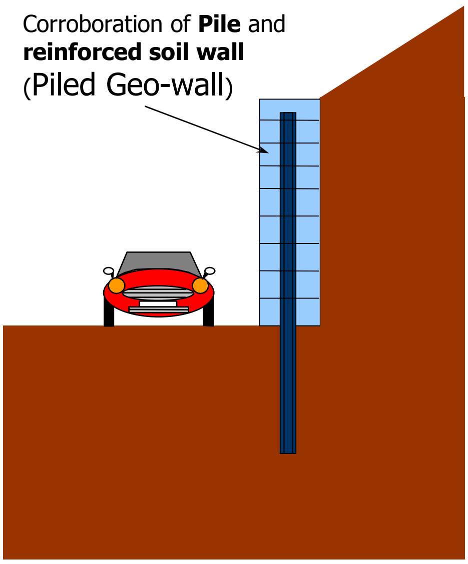


Figure 1: Image of Piled Geo-wall (PGW).

Therefore, a new type of independent reinforced soil wall with inserting piles into the Geo-wall body, as shown in Figure 1, which is referred to "Piled Geo-wall or PGW" in this paper, has been developed. The practicability of Piled Geo-wall to diverse structures has been already confirmed from three experimental studies with full-scale static and impact loading tests and a dynamic centrifuge model test (25G) were carried out in the past years [1], [2]. Recognizing the practicability, a study on simple design method to apply Piled Geo-wall to earth-retaining walls, rock-fall protection walls, and seismic countermeasure walls of road embankment in order to reduce deformation of road surface, has been conducted. In this paper, because of paper limitation, simple external stability verification methods of Piled Geo-wall as well as the reproducibility of the experiments' results by using the proposed verification methods are introduced.

2. EXTERNAL STABILITY MODEL

Piled Geo-wall was devised from an assumption regarding the interaction between pile and Geo-wall body, which the Geo-wall body with high ductility is possible to transmit lateral forces to the piles despite large relative displacement between the pile and the Geo-wall body as shown in Figure 2. Hence, in the design, the responses of the pile and the Geo-wall body have to be estimated respectively. Figure 3 shows the proposed simple estimation model of the responses of the pile and the Geo-wall body of Piled Geo-wall.

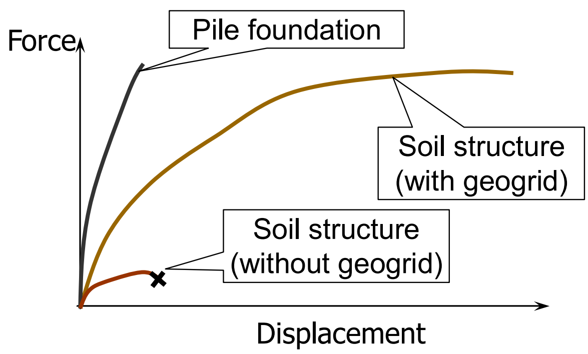
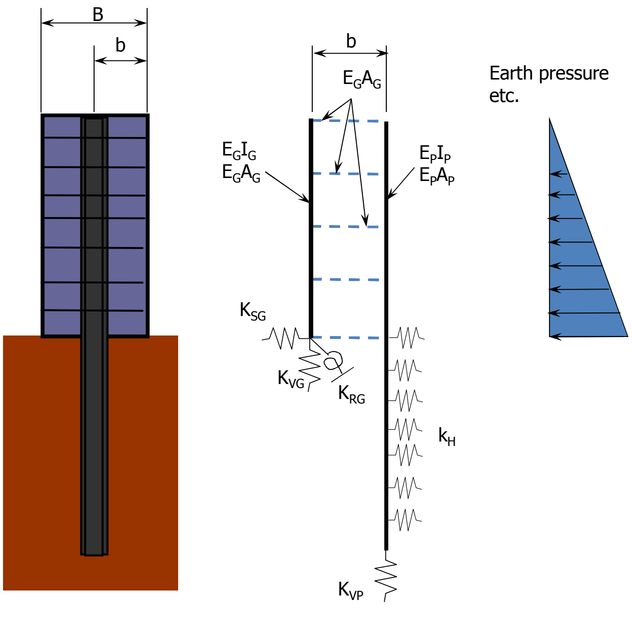
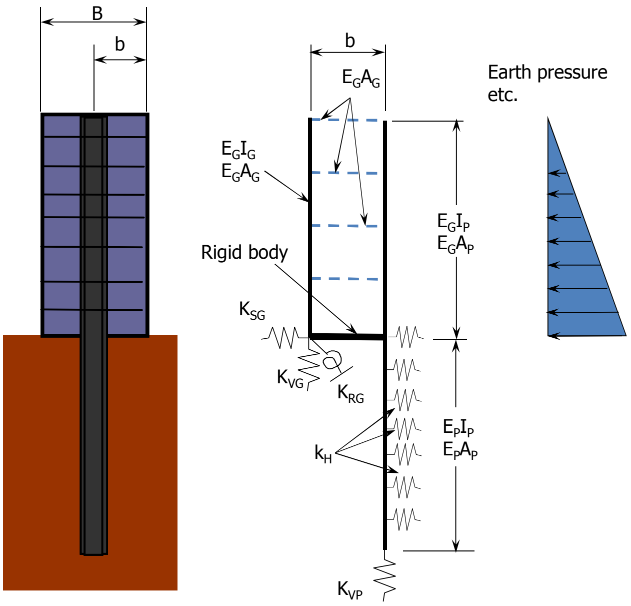


Figure 2: Interaction image between Pile and Geo-wall.



(a) Pile response estimation model



(b) Geo-wall body response estimation model

Figure 3: External stability model.

Where, E_PI_P, E_GI_G: flexural stiffness of pile and Geo-wall (kNm^2/m), E_PA_P, E_GA_G: compressional stiffness of pile and Geo-wall (kNm^2/m), E_GI_P: extent without considering flexural stiffness of pile, k_H: elasto-perfectly plastic spring constant of horizontal subgrade reaction (kN/m) set from (1), the limited value of k_H is passive earth pressure, K_{VG}: elasto-perfectly plastic spring constant of vertical subgrade reaction beneath the Geo-wall body (kN/m) set from (2), the limited value of K_{VG} is ultimate bearing capacity, K_{SG}: elasto-perfectly plastic spring constant of horizontal shear reaction beneath the Geo-wall body (kN/m) set from (3), the limited value of K_{SG}, S_{max}, is set from (4), K_{RG}: elasto-plastic rotation spring constant beneath the Geo-wall body (kN/rad) set from (5), the limited value of K_{RG} is determined by the ultimate bearing capacity, K_{VP}: elasto-perfectly plastic vertical spring constant beneath the pile (kN/m) set from (6), the limited value of K_{VP} is the ultimate bearing capacity of pile, k_h and k_v: coefficients of horizontal and vertical subgrade reaction (kN/m^3) in normal time or seismic situation, which are estimated from Specifications for Highway Bridges (Part IV) [3], D: pile diameter (m), d_u: unit depth, namely 1.0m, A_G and A_P: cross section areas of the Geo-wall body and the pile (m^2), c and ϕ: cohesion and shear resistance angle of foundation ground (kPa and rad).

$$K_H = k_h \cdot D \cdot d_u \quad (1)$$

$$K_{VG} = k_v \cdot A_G \quad (2)$$

$$K_{SG} = 1/3 \cdot k_v \cdot A_G \quad (3)$$

$$S_{\max} = c \cdot A_G + \sigma \cdot \tan\phi \quad (4)$$

$$K_{RG} = k_v \cdot b \quad (5)$$

$$K_{VP} = k_v \cdot A_P \quad (6)$$

3. PRACTICABILITY OF THE MODEL

3.1 Reproducibility of Static Loading Test

The summary of the static loading test of Piled Geo-wall [1], which is targeted for verification of the practicability of the proposed external stability model to the design of earth retaining wall in normal time situation, is shown in Figure 4.

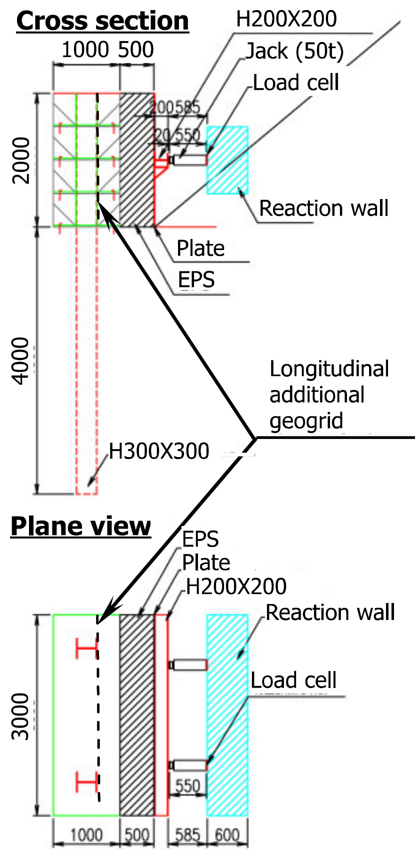


Figure 4: Summary of target static loading test.

Figure 5 shows the results of dynamic penetration tests converted to N value of standard penetration test (SPT) as the ground condition of the test. In this verification, the results of PD-2 obtained at the vicinity point of the target Piled Geo-wall was referred.

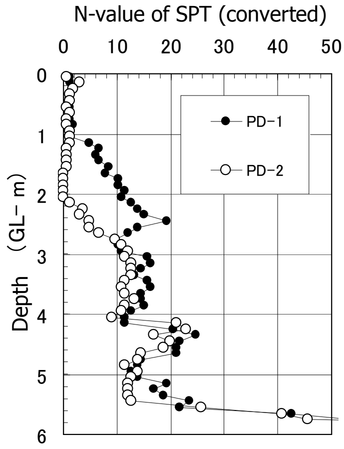


Figure 5: Ground condition.

Figure 6 shows the analysis results of the relationship between static load and displacement of Piled Geo-wall, top of the pile and Geo-wall body, which are compared with measured value from the test. And Figure 7 shows comparisons with the analysis results of maximum response of pile and measured ones from the test. According to the results, it is confirmed that the proposed model can reproduce the response of Piled Geo-wall and relative displacement between pile and Geo-wall body.

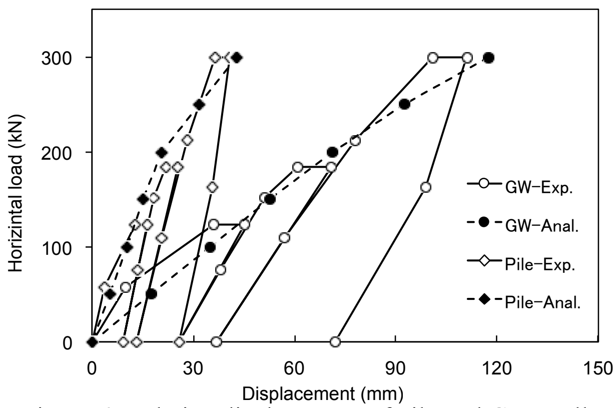


Figure 6: Relative displacement of pile and Geo-wall.

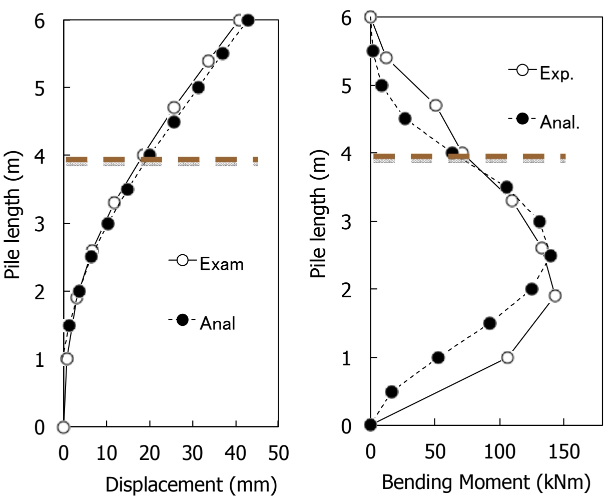


Figure 7: Maximum response of pile.

3.2 Reproducibility of dynamic centrifuge test (25G)

Figure 8 shows the transverse section of the model adopted in the dynamic centrifuge test (25G) [2], which is targeted for verification of the practicability of the proposed external stability model to the design of earth retaining wall in seismic situation. In this test, Piled Geo-wall was adopted as a seismic countermeasure for prevention of large deformation of the road embankment built on a slope. Slop ground was made up of cement-stabilized soil and, the soil of the embankment and the Geo-wall body was compacted with density control. Geotechnical and structural parameters converted to actual scale are presented on Table.1 and 2, respectively. Figure 9 shows the input earthquake wave converted to actual scale.

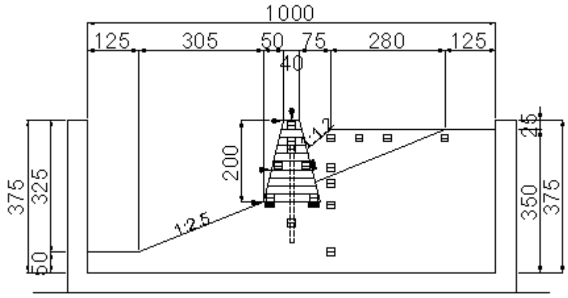


Figure 8: Model of dynamic centrifuge test (25G).

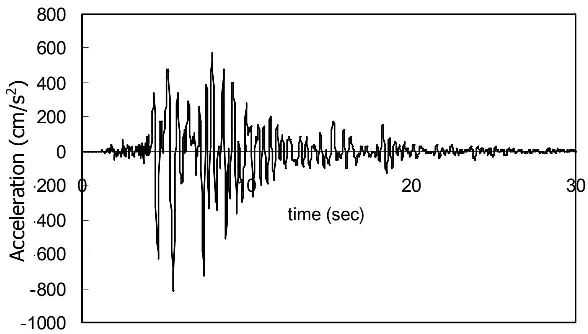


Figure 9: Input earthquake.

Table 1: Geotechnical parameter.

	E_0 (kPa)	c (kPa)	ϕ (deg)
Slope	3.26 x 10^5	55	0
Embankment	3.0 x 10^4	0	40
Geo-wall	3.0 x 10^4	0	40

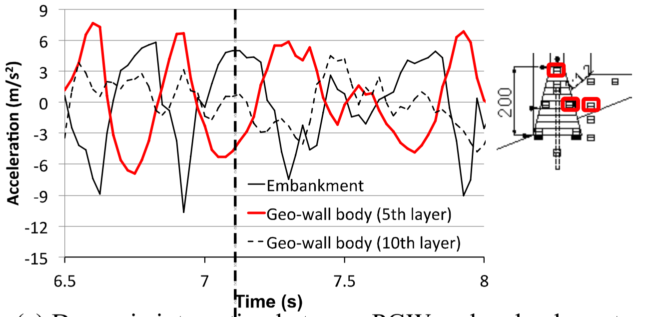
E_0: deformation modulus, c: cohesion, ϕ: shear resistance angle

Table 2: Structural parameter.

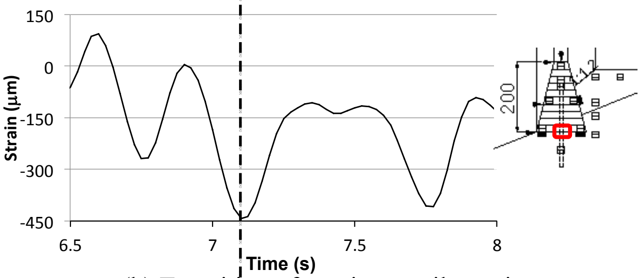
	E (kPa)	A (m^2/m)	I (m^4)
Pile	2.0 x 10^8	4.79 x 10^{-3}	2.04 x 10^{-4}
Geogrid	8.0 x 10^5	1.0 x 10^{-3}	-

E: Young modulus, A: sectional area, I: moment of inertia

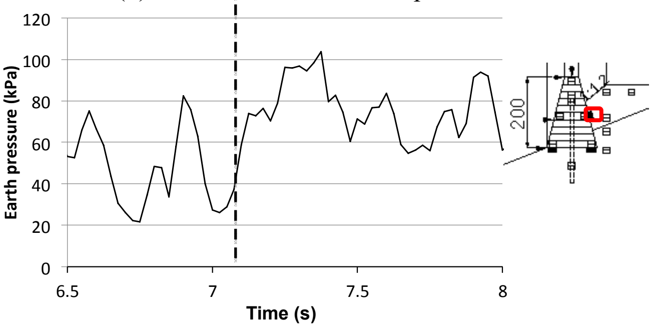
Because recognizing of dynamic interaction between structure and surrounding ground is necessary in order to design the structure by static analysis, dynamic interaction between the Piled Geo-wall and the embankment, transition of pile response and earth pressure at the embankment side of the Piled Geo-wall at the time that the maximum pile response was obtained are shown in Figure 10.



(a) Dynamic interaction between PGW and embankment



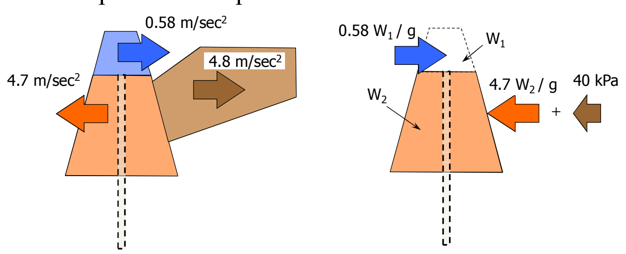
(b) Transition of maximum pile strain



(c) Transition of earth pressure

Figure 10: Dynamic responses.

According to the results, the antiphase between the response of Geo-wall body at 5th layer (the part with inserting pile) and ones of embankment and Geo-wall body at 10th layer (the part without inserting pile) is confirmed. And the states of inertia forces and earth pressure acting on the embankment side of Piled Geo-wall body at the time that the maximum pile response was obtained were confirmed as shown in Figure 11. Figure 12 shows comparisons of the maximum response of the pile, which analyzed one by the confirmed load states and obtained one from the experiment. From this result, it could be confirmed that the proposed estimation model can reproduce well the actual response of the pile of the Piled Geo-wall.



(a) Dynamic interaction (b) Load situation

Figure 11: Design situation.

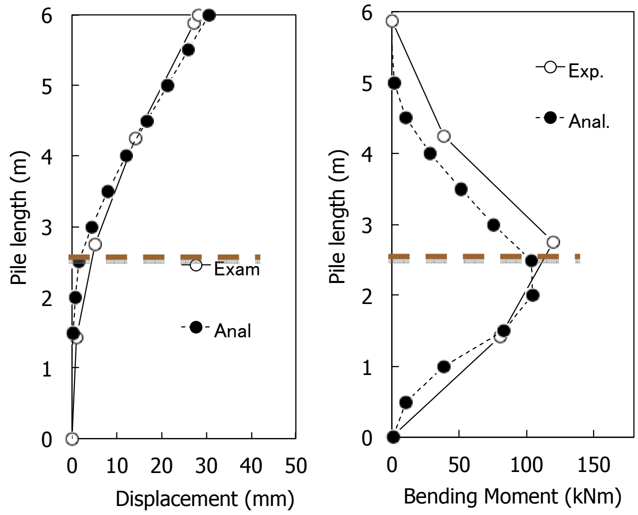


Figure 12: Maximum response of pile.

3.3 Reproducibility of impact loading test

The impact-loading test of Piled Geo-walls [1], which is targeted for verification of the practicability of the proposed external stability model to the design of rock-fall protection wall, is shown in Figure 13.

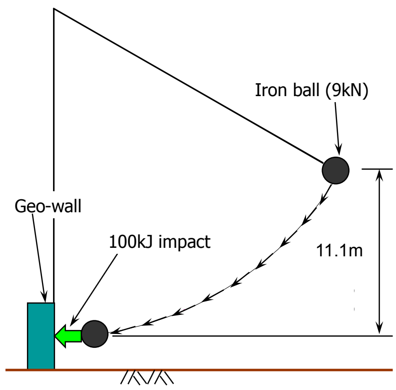


Fig. 13. Impact-loading test.

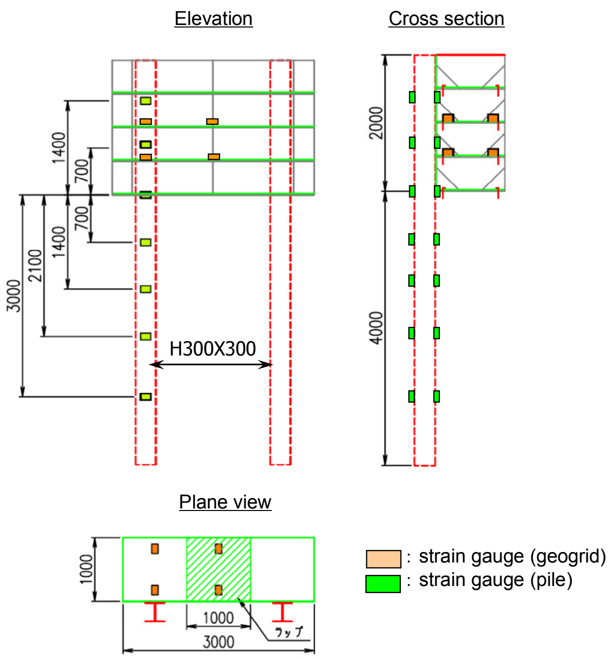


Figure 14: Structure and measurements of PGW-2.

In this verification, the results of two impact-loading tests to actual scale models, one is adopted in the static loading test (PGW-1) shown in Figure 4 and another is a new one (PGW-2), are targeted. The piles of PGW-2 are installed at outside of Geo-wall as shown in Figure 14, are adopted. Figure 15 shows proposed conversion procedure of design static load from impact-load in this study.

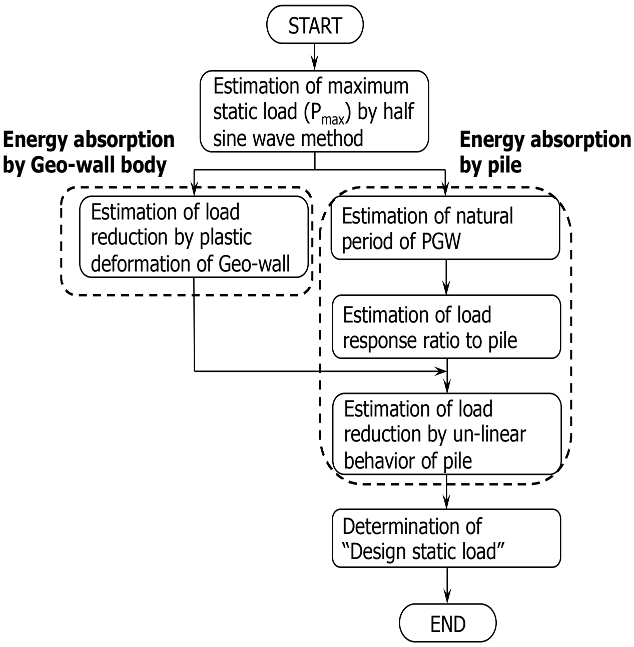


Figure 15: Conversion procedure of design static load.

Where, the maximum static load (P_{max}) based on half sine wave method is estimated by (8). In this equation, m is mass, V_0 is initial velocity (m/sec) at the time of the rock-fall impact to the Geo-wall body, which is predicted by (9), T is sustaining period (sec) of the impact by PGW, which is assumed as 0.07sec from the experiments, g is G-force, h is falling height of the rock fall.

$$P_{\max} = \frac{\pi \cdot m \cdot V_0}{T} \quad (8)$$

$$V_0 = \sqrt{2 \cdot g \cdot h} \quad (9)$$

Energy absorption by Geo-wall body was assumed as follows;

a. The displacement-time relationship of the iron ball and the pile obtained from the experiment is converted to the load reduction-time relationship as shown in Figure 16. The maximum load reduction is the maximum static load estimated by (8). Load reduction by pile is assumed from inverse analysis with using proposed external stability model, because high reproducibility of the static loaded pile displacement by using the proposed model was confirmed at the section "3.1".
b. The iron ball displacement expresses entire energy absorption, thus the difference of entire load reduction and one of pile was assumed as the reduction load by plastic deformation of Geo-wall body.
c. From the abovementioned result, the relationship between load reduction ratio and plastic displacement of Geo-wall body was assumed as (10).

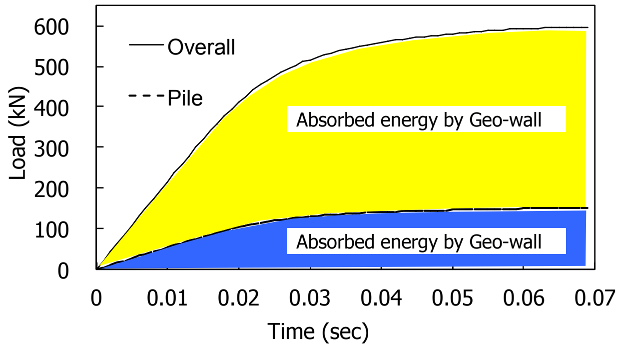


Figure 16: Load reduction-time relationship.

$$c_{RP} = 9.8 \cdot \delta \cdot (\delta - 0.144) \qquad (0.15 \leq \delta) \quad (10)$$

$$\delta = P_{\max} / K_s \quad (11)$$

$$P_{R\max} = P_{\max} \cdot (1 - c_{RP}) \quad (12)$$

Where, c_{RP}: load reduction ratio caused by plastic deformation of Geo-wall body, δ: plastic deformation of Geo-wall body (m) estimated by (11), K_s: equivalent plastic spring constant with respect to inserting rock-fall into Geo-wall body (kN/m), which is assumed as 1650kN/m from the experiments, P_{Rmax}: reduced static load with considering energy absorption by Geo-wall.

The values of the impact period (T) and the equivalent plastic spring constant (K_s) are considered as variables depending on stiffness of the Geo-wall body and so on, but because the stiffness would not be so large different one if it is similar scale PGW with experiment one, it is considered that the values can be applied to small type of PGW.

Load response ratio to pile expresses reduction (or amplification) effect of transmitting load to pile. It is well known that the response reduces if the structure with long natural period receives the impact load with short impact period; in contrast, the response amplifies if the structure with short natural period receives the impact load with comparative long impact period. Therefore, the coefficient considered the characteristics in case of using load estimated from half sine curve method was proposed, as (13), from the past study [5]. According to the past study, the border of reduction and amplification of the response is said to be the case that the ratio of impact period of road and natural period of structure is about 0.26.

$$c_{res} = -4 \cdot r_t \cdot (0.6 \cdot r_t - 1.1) \quad (13)$$

$$r_t = T / t \quad (14)$$

$$P_{RES} = P_{R\max} \cdot c_{res} \quad (15)$$

Where, c_{res}: load response ratio to pile, r_t: the ratio of impact period of road and natural period of pile, as (14), t: natural period of pile (sec), P_{RES}: load transmitting to pile (kN). And finally, the design static load (P_D) is determined from the load reduction, which is estimated by equivalent energy method [6] of both elastic and elasto-plastic analyses with using the proposed external stability model. Figure 17 shows an example of equivalent energy method applied to PGW design.

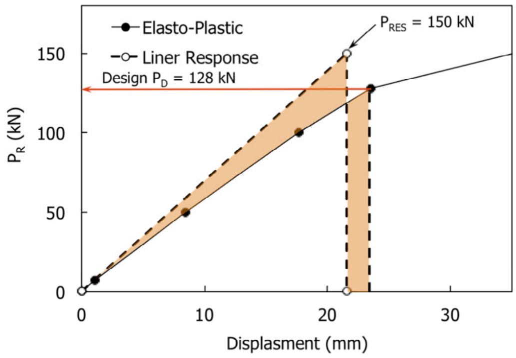


Figure 17: An example of equivalent energy method.

Figure 18 and 19 show the maximum pile responses of PGW-1 and 2, respectively. According to the results, it can be confirmed that the proposed external stability model reproduces well ones obtained from the experiments. Where, although it is no wonder that analyzed pile top displacements match up to obtained ones because the energy absorption of Geo-wall body was determined from inverse analysis of pile, the reproducibility can be confirmed from the distribution in depth of the displacement and the bending moment of piles.

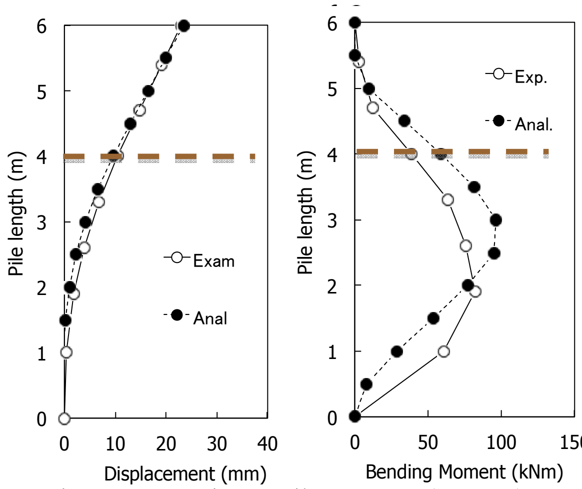


Figure 18: Maximum pile response (PGW-1).

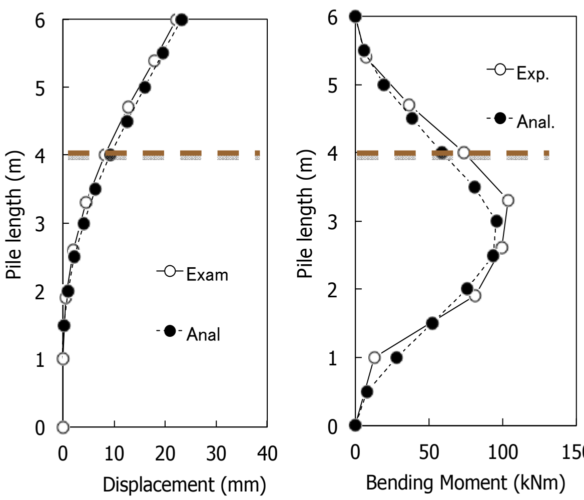


Figure 19: Maximum pile response (PGW-2).

4. CONCLUSIONS

The contents of this paper are concluded as follows;

- Simple external stability model of Piled Geo-wall for practical design was proposed.
- The practicability of the proposed design model was confirmed from good reproducibility of real response obtained from full-scale static and impact loading tests, and a dynamic centrifuge model test.
- In the design on Piled Geo-wall in static load situation, high reproducibility of interaction between pile and Geo-wall body as well as one of pile response were confirmed.
- In the design on Piled Geo-wall in seismic situation, it was confirmed that safety design can be executed in case with design load situation as well as high reproducibility of the pile response in case with real load situation.
- In the design on Piled Geo-wall for rock-fall protection, conversion procedure of design static load from impact one was also proposed and its practicability was confirmed from good reproducibility of pile response by using the proposed procedure.

The following issues, however, have to be conducted to apply the proposed model to more wide condition of Piled Geo-wall.

- Design on large scale (width, height) Piled Geo-wall.
- Application of steel-pipe pile to Piled Geo-wall.
- Improvement of static load conversion procedure from impact one

5. REFERENCES

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Pertinent discussion including authors' closure, if any, will be published in the June 2014 if the discussion is received by Dec., 2013.
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