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Technical Report

Development of the "Combi-Gyro Method," a New Steel Wall Construction Method Combining Steel Sheet Piles and Pipe Piles

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Abstract

The Combi-Gyro method is a novel construction method of earth retention walls. By the combination of Hat-type steel sheet piles excellent in water tightness and steel pipe piles of high rigidity, the method offers walls of rational structure in the strength range of small diameter pipe piles, where steel walls were not cost-competitive. The method uses a new type of driving machine for both sheet piles and pipe piles. The results of pile driving and real-size excavation tests and the design and work methods for the Combi-Gyro method established through these tests are presented herein.

1. Introduction

Owing to excellent drivability and economic efficiency, steel sheet piles have been widely used for permanent structures such as port construction, river revetments, etc. as well as for temporary structures such as earth or water cut-off walls. When lateral rigidity larger than that of sheet piles is required, for instance, for tall walls for temporary earth guard for deep excavation work or river revetments, port piers, etc., steel-pipe sheet piles have been employed. While pipe sheet piles have rigidity and bearing capacity higher than those of common sheet piles, pipe sheet piles are manufactured by longitudinally welding coupling joints to the pipe wall to join them to each other, and when the pipe diameter is 800 mm or less, the number of coupling joints per wall length increases, raising the pile manufacturing costs, and the wall may become more expensive than concrete walls or those by other methods.

In consideration of the above, we developed the Combi-Gyro method suitable for constructing steel wall structures economically. It is a novel wall construction method combining Hat-type steel sheet piles [1)] having the largest sectional width of any rolled profile steels with high-rigidity steel pipe piles, using one driving machine for press driving of sheet piles and for rotation-press driving, the Gyropress method™, [2)] of pipe piles.

This paper presents the principal results of the studies into the performance of the developed method that allows wider application of the steel pile products, that is, the results of the pile driving test and actual-size excavation test using a newly designed piling machine for the two types of piles, the field construction work, and the wall design method according to the developed method.

2. Outlines of Developed Wall Construction Method

2.1 Sectional structure of wall

Figure 1 shows the sectional structure of a wall according to the Combi-Gyro method. Steel pipe piles are arranged to fill in the recesses of the wall of the sheet piles, and thus, while the sheet piles stop the flow of earth and underground water making use of their coupling joints of excellent water-tightness, the pipe piles are mainly responsible for resisting the pressure of earth and water. The interval between the pipe piles can be selected at the designer's discretion, but if it is too large, the lateral stiffness of the sheet-pile wall

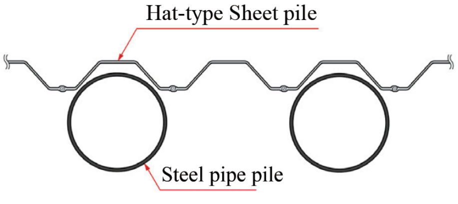

Fig. 1 Cross-section of wall made by Combi-Gyro method

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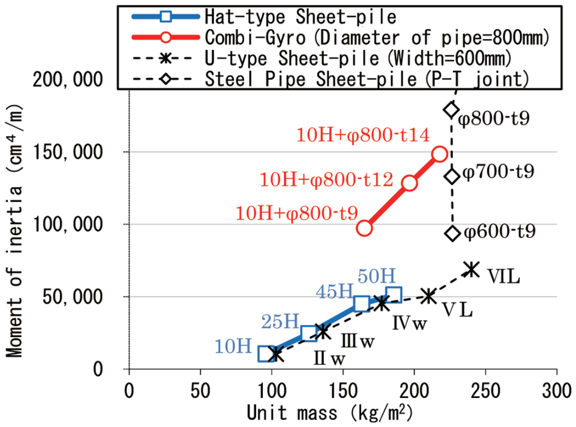

Fig. 2 Relationship between steel weight and sectional performance

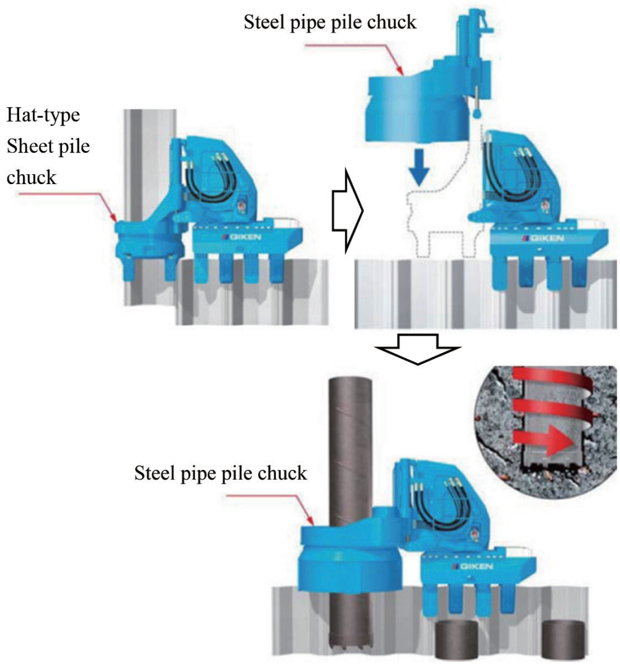

Fig. 3 Construction process of Combi-Gyro method [3)]

becomes uneven. The standard design is, thus, to provide a pipe pile for every two sheet piles.

Figure 2 shows the relationship between the steel weight and the sectional moment of inertia of the wall structures of steel sheet piles and pipe piles by the Combi-Gyro method. Here, the steel materials used are pipe piles 800 mm in diameter, of different wall thicknesses, and SP-10H sheet piles having a length roughly 70% that of the pipe piles, and the lateral stiffness of the wall is evaluated considering only the pipe piles. Figure 2 clearly shows that, in the range of lateral rigidity of wall structures obtainable with small-diameter steel-pipe sheet piles, the total steel weight is decreased by applying the Combi-Gyro method.

2.2 Wall construction by Combi-Gyro Method

2.2.1 Outlines of site construction work

By the present method, Hat-type steel sheet piles are continuously driven into soil using a driving machine specially designed for this type of sheet pile; here, previously driven piles are used as reaction piles. As seen in **Fig. 3**, [3)] steel pipe piles are driven using the same driving machine: after driving sheet piles to form a wall, the pile holder (chuck) of the machine for sheet piles is changed with another for pipe piles, and pipe piles are driven under rotation and pressing, using the sheet piles as reaction piles. Since sheet piles having comparatively small sectional areas are used as the reaction piles, pipe piles are driven under rotation and pressing to prevent them from being pulled up by the reaction force with the same high driving efficiency as that of the Gyropress method™.

Photo 1 Construction test of Combi-Gyro method

Photo 2 Cutting bits at lower end of pipe pile

2.2.2 Pile driving test

To confirm the performance of the driving machine for the present method, piles were driven into real soil for test purposes as shown in **Photo 1**. The piles used for the test were SP-10H Hat-type steel sheet piles 10.0 m in length, and pipe piles 800 mm in diameter, 9 mm in wall thickness and 12.0 m in length, having bits at the lower end to cut into soil under rotation (see **Photo 2**). During the test, no sheet piles used as the reaction piles for driving pipe piles were found to come up under the upward reaction force, and during the rotation driving of the pipe piles into a gravel layer having a maximum N value of roughly 50, no great increase was seen either in the downward pressing force or the rotating torque, and the driving time of the pipe piles was stably 28 min each (**Fig. 4**).

3. Design Philosophy

3.1 Confirmation of design load and stress

As seen in **Fig. 5**, according to the present method, steel pipe piles are exposed at the front side (visible side) of a wall, and thus a wall constructed by the method is designed such that the loads of earth and underground water are borne by the pipe piles, the sheet piles serving as a load transfer plate.

As there is a pipe pile for every two Hat-type steel sheet piles, each pipe pile is considered to bear the pressure of the earth and water in a wall section 1.8 m in width, equal to the pipe pile pitch. Although the basic arrangement is that pipe piles are on the front side

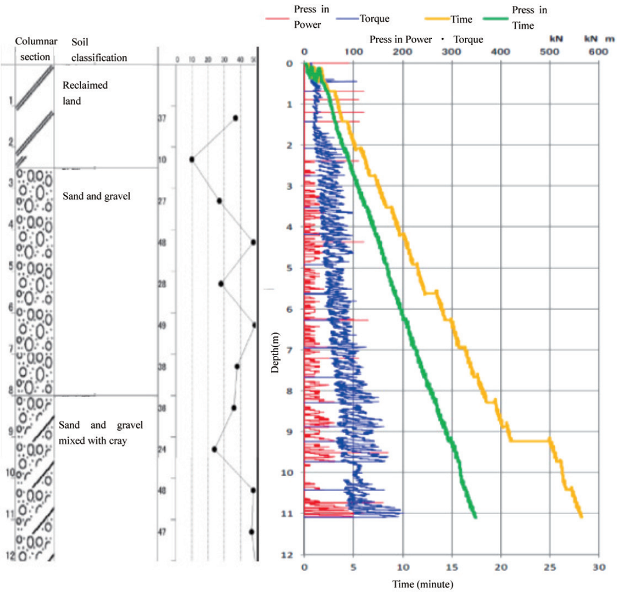

Fig. 4 Relationship between ground condition and construction data of press-in

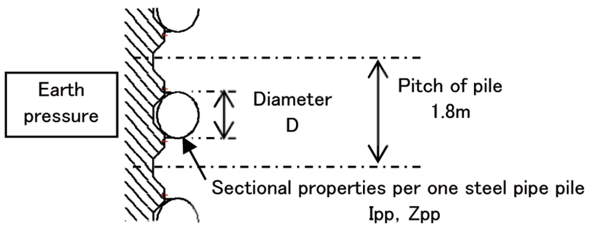

Fig. 5 Cross section of wall by Combi-Gyro method

of the wall to be constructed, when it is necessary to have the sheet piles on the front side for reasons of appearance or corrosion protection, the pipe piles may be driven on the back side. It has to be noted however, that in this case, it is necessary to tie the tops of the sheet piles to those of the pipe piles using steel plates or similar, and in addition, to study the stability of the sheet piles being embedded into the soil. The stress on the sheet piles can be estimated by sectional calculation assuming that the entire pressure of the earth and water is imposed on a simple beam supported at the top and the design ground level.

The calculation model for the design of a wall by the Combi-Gyro method is given in **Fig. 6**. As stated earlier, it is assumed here that each pipe pile bears the pressure of the earth and water imposed on a wall width of 1.8 m, the pitch of the pipe piles, and that the entire pressure of the earth and water is imposed on a simple beam of sheet piles supported at the top and the design ground level.

3.2 Pile penetration

3.2.1 Penetration of pipe piles

The embedding depth of the pipe piles by the Combi-Gyro method can be calculated, as in the case of ordinary sheet pile walls, using Chang's equation. The property value β of a pipe pile used in the equation is obtained from the horizontally acting subgrade reaction. Here, with respect to the portion of the pipe pile penetration into soil overlapping with that of the sheet piles, β_w below is calculated, and with respect to the balance, β_p is calculated. The concept of the property value β of a pipe pile according to the Combi-Gyro method is given in **Fig. 7**.

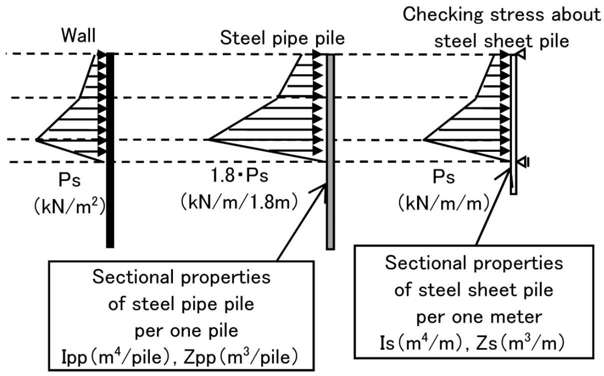

Fig. 6 Design calculation model of Combi-Gyro method

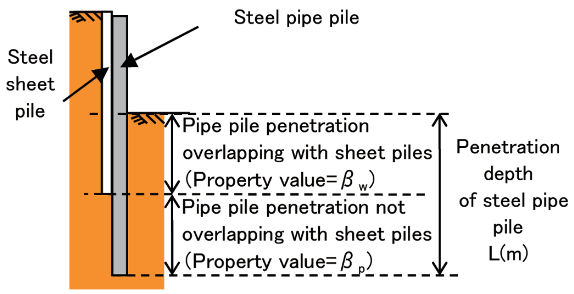

Fig. 7 Way of thinking of the property value β

The said β_w and β_p are obtained using the equations given below. For the pipe pile penetration into soil overlapping with that of the sheet pile, the loading width is set equal to the pitch X of the pipe piles, and for the balance not overlapping with the sheet piles, the loading width is set equal to the diameter D of the pipe piles.

$$\beta_w = \sqrt[4]{\frac{k_H X}{4EI_{pp}}} \quad (1) \qquad \beta_p = \sqrt[4]{\frac{k_H D}{4EI_{pp}}} \quad (2)$$

here, k_H is the horizontal subgrade reaction coefficient, E the elasticity modulus of the steel materials, I_{pp} the second moment of the area of each pipe pile. When the pipe piles are assumed to be driven to a semi-infinite depth, their penetrating length L has to be set equal to or more than $3/\beta$ using the above property value of the pipe pile.

3.2.2 Penetrating depth of sheet piles

When pipe piles are on the front side, the sheet piles are supported by them at the lower end, and the penetrating depth of the sheet piles can be defined from the length required for boiling-heaving, in consideration of the position where active and passive earth pressures are in equilibrium.

4. Actual-size Pile Driving and Excavation Test

To collect data on the behavior of walls erected by the Combi-Gyro method, a test was conducted, wherein two walls were built in parallel to each other using SP-10H Hat-type steel sheet piles and pipe piles 800 mm in diameter and 9 mm in wall thickness, and the ground between the two was dug to a depth of 4.5 m below the ground level. One of the two walls had pipe piles on the front side (excavation side) of the sheet piles, and the other on their back side. Based on a boring test the type of soil used was sand, the average N value above the excavation level was 14, and the same below it was 8. The ground water level was measured near the excavation sur-

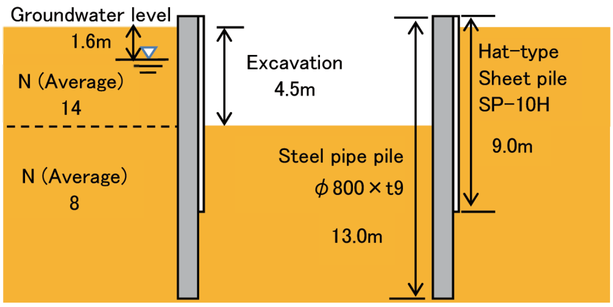

Fig. 8 Test outline

Photo 3 Actual excavation test

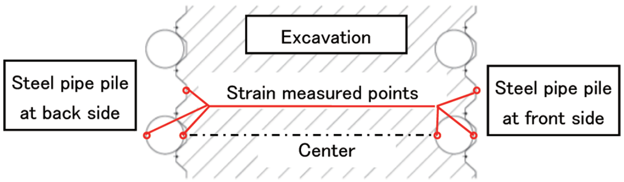

Fig. 9 Distortion measurement position of steel materials

face, and it was 1.6 m below the ground level after the soil between the walls was dug to 4.5 m below the ground level. **Figure 8** shows the outline of the test, and **Photo 3** some of the test situations. As for the distortion of the sheet piles and pipe piles, the vertical distortion of the walls was measured at their width centers as shown in **Fig. 9**; note that the distortion of the pipe piles was measured both on the front and the back sides.

The design calculation was made for the two walls on the assumption that the total pressure of the earth and the underground water was borne by the pipe piles, regardless of whether they were on the front or the back side, and the results were compared with the actually measured dislocations. In the design calculation, the earth and the underground water pressures were taken into account down to the virtual ground level, or the depth where the sum of the active earth pressure and the residual water pressure balanced with the passive earth pressure, and further down, the recoiling reaction force of the soil was assumed to be dominant. The stress-strain relationship of the sheet piles was calculated assuming that the above earth pressure and water pressure were imposed on a simple beam supported at the head and the virtual ground level, and the stress-strain thus obtained was compared with the measured strain.

The soil condition for the design calculation was set as follows: the moist unit weight γ = 18 kN/m^3, the unit weight in water γ' = 9 kN/m^3, the angle of wall friction δa = 15°, δp = −15°. The angle of internal friction ϕ was calculated as follows assuming that the average N value was 14:

$$N_1 = \frac{170\,N}{\sigma_v' + 70} = \frac{170 \cdot 14}{50 + 70} = 19.8 \quad (3)$$

$$\phi = 4.8 \log_e N_1 + 21 = 35$$

where, σ_v' is the effective pile head load (kN/m^2) obtained on the occasion of the standard penetration test.

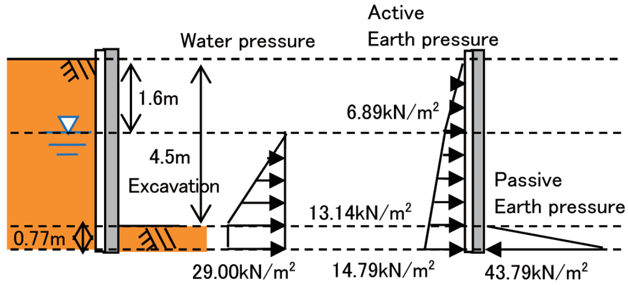

Fig. 10 Earth and water pressures acting on wall

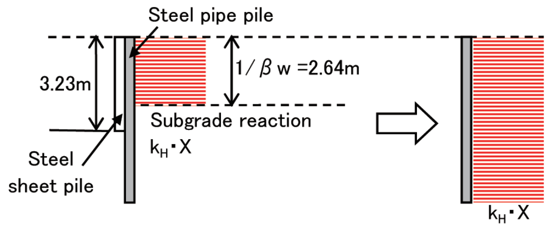

Fig. 11 Concept of subgrade reaction along pile penetration

Figure 10 shows the ground pressure and the water pressure acting on the wall. The coefficient of subgrade reaction k_H of the wall portion buried in soil is calculated according to the Design Guidelines on Post-disaster Construction and Damage Repair[4] as follows:

$$k_H = 6910\,N^{0.406} = 6910 \cdot 8^{0.406} = 16\,100 \text{ kN/m}^3 \quad (4)$$

As stated in 3.2.1 above, assuming a pipe pile pitch of 1.8 m, the property value β_w of the pipe pile penetration portion overlapping with that of sheet piles is given as follows:

$$\beta_w = \sqrt[4]{\frac{k_H X}{4EI_{pp}}} = \sqrt[4]{\frac{16\,100 \times 1.8}{4 \times 2.0 \times 10^8 \times 1.75 \times 10^{-3}}} = 0.379 \text{ m}^{-1} \quad (5)$$

In the design of steel sheet-pile walls, it is often the case that the subgrade reaction of the soil portion between the ground level and $1/\beta$ has the largest influence on the wall behavior, and for this reason the average of the subgrade reaction of the soil portion is often used as the subgrade reaction of the entire pile penetration portion. The value of $1/\beta_w$ based on the property value β_w of the pipe pile described earlier is 2.64 m, which is smaller than the penetration depth 3.23 m of the sheet piles. This means that the entire depth portion from the virtual ground level to $1/\beta$ is included in the penetration portion of the sheet piles, and the subgrade reaction of the portion was considered to act on the penetration portion of the pipe piles. **Figure 11** shows the concept of the subgrade reaction of the penetration portion of the pipe piles.

The values obtained through the above calculations are compared with the measured values as shown in **Fig. 12**. Note here that the bending strain of a cantilever beam in the direction of the excavation is regarded as positive. The displacement at each measuring point was calculated from the pile head dislocation and the readings

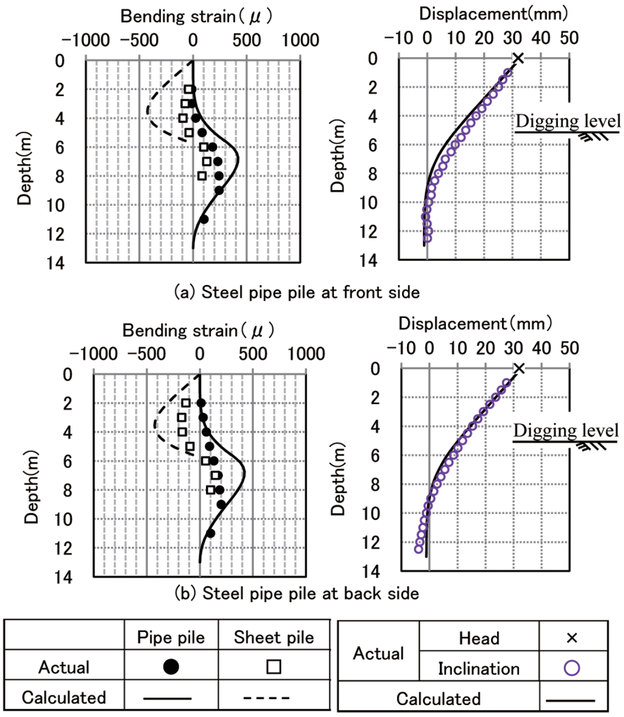

Fig. 12 Comparison between measured and calculated bending strains and displacements

of angle meters provided inside the pipe piles.

Figure 12 clearly shows that calculation under the assumption that the entire earth pressure and water pressure are borne by the pipe piles alone regardless of which side of the wall they are provided yields practically acceptable displacement values, and that the calculated strain tends to be larger than the measured one. The fact that the load borne by the sheet piles was not considered in the calculation made the calculated value larger, erring on the side of caution in the design.

Another point regarding sheet piles is that, in the depth range above the excavation level, there occurred a strain in the direction opposite to that of the pipe piles, indicating that the sheet piles were considered to have bulged toward the excavation in the portion between the pile head down to the excavation level. It follows, therefore, the assumption to the effect that the earth and water pressures act on a beam supported at the pile head and the virtual ground level makes it possible to express the mode of displacement above the excavation level. Thus, considering the wall portion between the heads and the virtual ground level as a single beam bearing the entire earth and water pressures in the design calculation ensures a safe design for steel sheet piles.

5. Conclusion

This paper presents the Combi-Gyro method, a new wall construction method using steel sheet piles and pipe piles. The method is expected to expand the application of these steel materials to earth retention walls, in the market sector where steel walls used to be inferior in terms of costs to other structure types.

Acknowledgements

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