The world's first steel sheet pile-based building structures "Sozokan"

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ABSTRACT

GIKEN LTD. has been developing press-in machines that utilize the "Press-in Principle," which can generate large amounts of energy from a small body of equipment using the force of the earth. The "Sozokan"* (The Museum of Piling Machines)," the building discussed in this paper, is a warehouse facility that traces the history of press-in machine development and uses steel sheet piles, which are closely associated with the press-in machine, as its main structural members. It is the first building in Japan to realize a large space by using steel sheet piles, which are normally used only for temporary earth-retaining walls and/or cofferdams, as the main structural members. The use of the 600mm width Hat shaped steel sheet piles (SM-J295), which is not normally employed as a material for building structural members, has been approved by the Minister in Japan after a performance evaluation by the Building Center of Japan. Since the frame plan and the concept of joints are different from those of ordinary steel structures, we proceeded with the design while seeking a structural design method unique to steel sheet piles and a construction method that takes advantage of the features of steel sheet piles. This paper describes the structural design method, structural analysis, and construction method of the "Sozokan" (The Museum of Piling Machines).

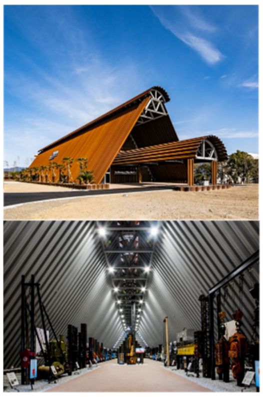
* "Sozokan" is the name of the facility made up of the Japanese words sozo (creation) and kan (hall).

Key words: *steel sheet pile, press-in method, steel structure, SMJ295 hat-shaped steel , large space*

1. Outline of the project

1.1. Background and objectives of the project

The "Press-in Principle" is a theory of driven-in piling that takes advantage of the forces of the earth. By utilizing the pull-out resistance force generated when a pile embedded in the ground is about to be pulled out, the next new pile can be statically pushed into the ground. GIKEN LTD. has been developing press-in machines that utilize this "press-in principle. The building discussed in this paper, the "Sozokan" (The Museum of Piling Machines), is a warehouse facility that traces the history of the development of the press-in machine, and its main structural members are steel sheet piles, which are closely associated with the press-in machine. It is the first building in Japan to create a large space by using steel sheet piles, which are usually used only for temporary earth-retaining walls and/or cofferdams, as main structural members. **Fig. 1** shows an overview of the "Sozokan". The interior space is an open space with no pillars for the display of the pile-driving machine. This paper describes the building's unique design and analysis method of steel sheet piles applied to the "Sozokan" and the construction method.



Building Outline
Site: Konan City, Kochi Prefecture
Building Use: Warehouse
Building area: 2,422.92m2
Total Floor Area: 1,496.86m2
Building Height: 18.07m
Building Length: 84.0m

Structural Outline
Structure: Steel frame
(main structure is steel sheet pile)
Frame type: Ramen structure
Columns and beams: Steel sheet pile and shaped steel
Column and beam joints: High-strength bolt friction joints
Foundation type: Direct foundation

Fig. 1 Building and Structural Outline

2. Structural Design Policy

2.1. Structural planning

As shown in **Fig. 2**, the building is composed of a ramen structure consisting of slanted wall, roof, end wall, and foundation. The ramen structure consists of a trapezoidal frame made of H-shaped steel, to which 20 m long steel sheet piles are attached to form a ramen structure. The end wall is structurally separate from the diagonal wall and is constructed together with the steel sheet piles that are buried underground. The foundation is a direct foundation with a 25mm steel plate connected to the bottom of the lean-to wall via a plate to receive the ground reaction forces. **Fig. 3** shows a cross-sectional view, and **Fig. 4** shows typical details of ①the end wall, ② ③ the diagonal wall, and ④ ⑤ the foundation.

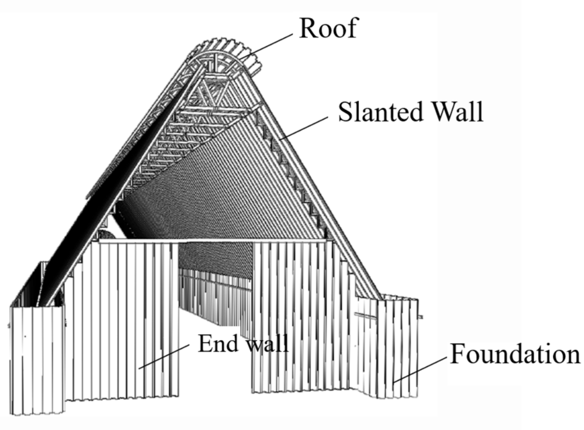


Fig. 2 Structural perspective

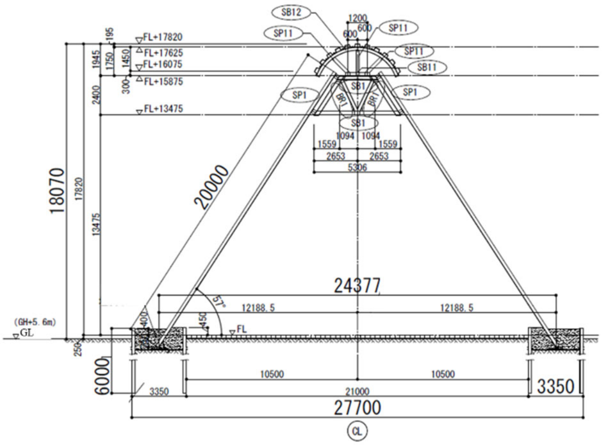


Fig. 3 Cross Section

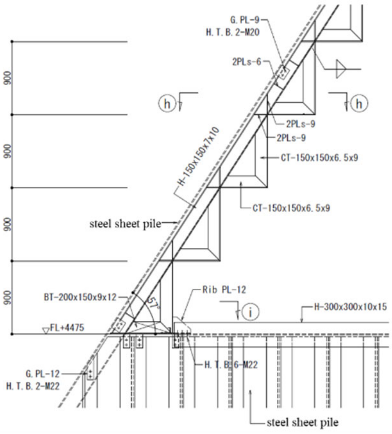


Fig. 4-1 End wall (Louver mounting part)

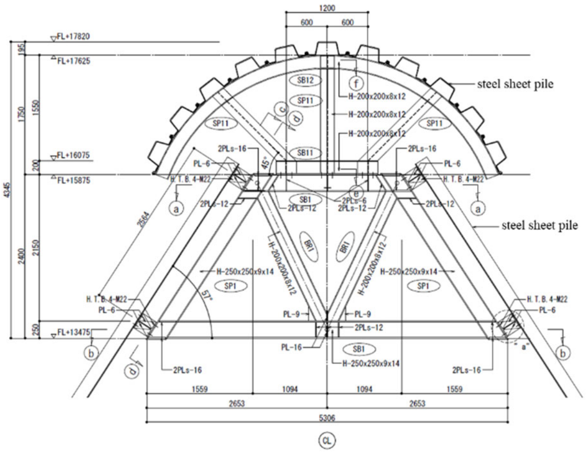


Fig. 4-2 Slanted wall section
(Trapezoidal frame mounting section)

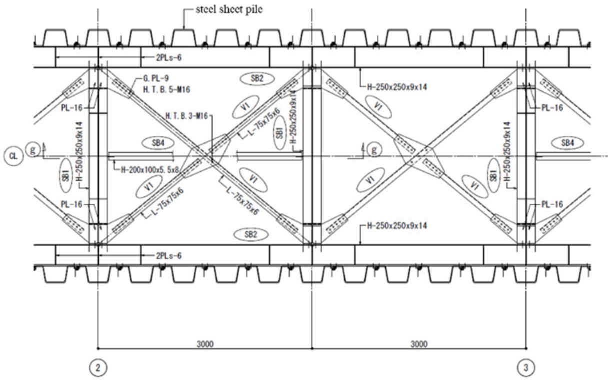


Fig. 4-3 Slanted wall section (Top of trapezoidal frame)

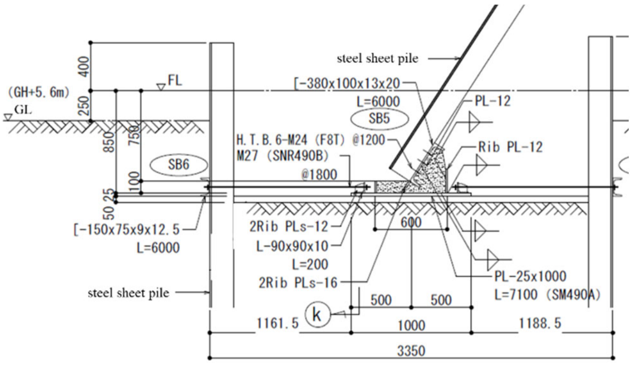


Fig. 4-4 Foundation part (Cross section)

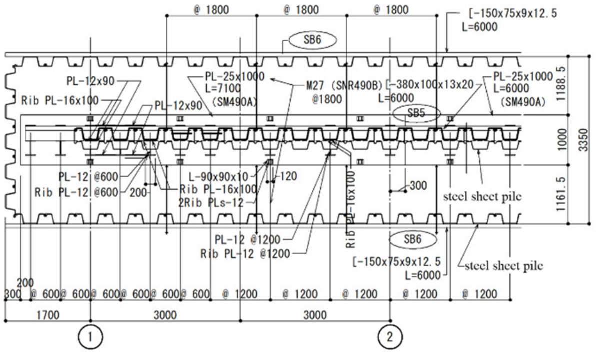


Fig. 4-5 Foundation plan (Cross section)

Fig. 4 Details of sheet pile layout

2.2. Design Criteria

To ensure that the components of the building will not be damaged in the event of a major earthquake and that the deformation of the building will be kept within the range where the exterior materials will not be damaged, the design criteria were set as follows.

- Main structure: within elastic limit capacity.
- Deformation angle 1/75 or less
  (within allowable deformation of exterior materials)
- Foundation : within short-term allowable stress

Typically, it is common practice to set the deformation criterion for steel structures at 1/100. However, after discussing with the review authority regarding safety, it was confirmed that the exterior materials could follow the deformation and remain undamaged even with a deformation of 1/75. Thus, the criterion was set accordingly.

3. Structural Analysis Model Overview

3.1. Modeling of steel sheet piles

Since steel sheet piles are not normally used for structural members of buildings, the structural properties of the steel sheet piles input into the analytical model are described. The steel sheet pile used in this building is SM-J295 hat-shaped steel, which is a material specified in the Article 37 of the Building Standards Act of Japan for use in building basement exterior walls. The steel sheet piles will be used for the building frame, so the cross-sectional specifications should be made in consideration of corrosion. **Table 1** shows the materials used for this building. **Table 2** shows the cross-sectional specifications of the steel sheet piles after reducing the thickness by 1 mm on one side and a total of 2 mm on both sides. As shown in **Fig. 5**, the steel sheet piles are connected with each other by fitting, but there is a certain separation between the two, the stress transfer between the members is assumed to be negligible.

Table 1. Materials used

Areas of the building	Shape	Standard	Grade
Roof and Slanted Wall	Hat-type Sheet Piles (SM-J295)	N/A	SYW295
	H-beams, Equal-angle steel	JIS G3101	SS400
	H-beams	JIS G3136	SN490B
Foundation	Hat-type Sheet Piles (SM-J295)	MSTL-0148 (Ministerial Authorization)	SYW295
	H-beams, Steel Plate	JIS G3101	SS400
	Steel Plate	JIS G3106	SM490A

Table 2. Cross-sectional properties of steel sheet piles considering corrosion

Sectional Performance			Corrosion	
			without	with
Width	B	cm	60.0	-
Height	D	cm	20.0	-
Area	A	cm^2	111.2	94.5
Moment inertia	I_y	cm^4	7,250.0	6,180.0
	I_z	cm^4	39,932.8	33,942.9
Section modulus	Z_y	cm^3	705.0	599.3
	Z_z	cm^3	1,254.1	1,066.0
Radius gyration	i_y	cm	8.1	-
	i_z	cm	19.0	-

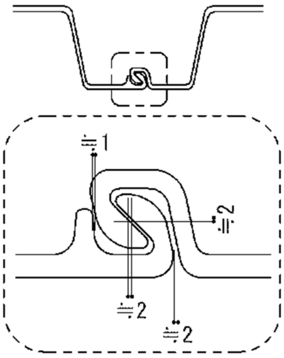


Fig. 5 Interlock(ing) of steel sheet pile

3.2. Modeling of girders

Fig.6 and **7** shows the structural analysis model used in the design of this building. The following is a description of the rules used in the development of the structural analysis model.

A linear analysis was used, assuming that the members remain within their elastic range even in the event of a major earthquake.

A trapezoidal frame trusses (referred to as a trapezoidal frames) were constructed every 3 m in the girder direction, and the load is supported by this trapezoidal frame and the transverse members were connected to the trapezoidal frames in the girder direction (**Fig. 7**).

The joints between the transverse members and the steel sheet piles are modeled by a very rigid connection that mimics the bolt-to-bolt distance of steel sheet piles, with pins at the ends of the joints between the members and the transverse members (**Fig. 7**).

The steel sheet piles in the diagonal walls are assumed to be free from lateral buckling due to their mutual buckling, and rotation around the global Z-axis (torsion in the direction of the sheet pile axis) is constrained in the analysis.

The support force is calculated by assuming that the XY direction is restrained, and the Z direction is a nodal spring based on the ground spring constant at the support point of the leg (**Fig. 8**).

The nodal ground spring is set as ground spring constant $K = q/S_E$ [kN/m3] by calculating the immediate settlement SE [m] by elastic theory.1)

The roof load is evaluated as a mass weight on a trapezoidal frame.

For steel sheet piles, trapezoidal frames, and foundation girders, the self-weight is evaluated on the model. In addition, the calculated value shall be multiplied by 1.05 to account for joint members.

The weight and dead weight of the masses are assumed to be 1.0 times the vertical downward direction for long-term loading, and 0.9 times the horizontal and vertical downward direction for seismic loading, considering horizontal and vertical movements (considering the regional coefficient Z=0.9 in Kochi Prefecture).

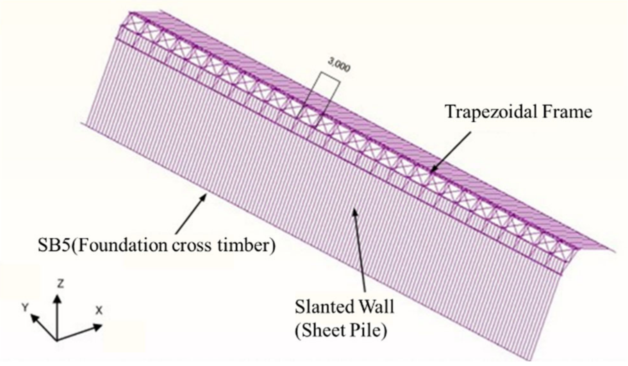


Fig. 6 Overall model for structural analysis

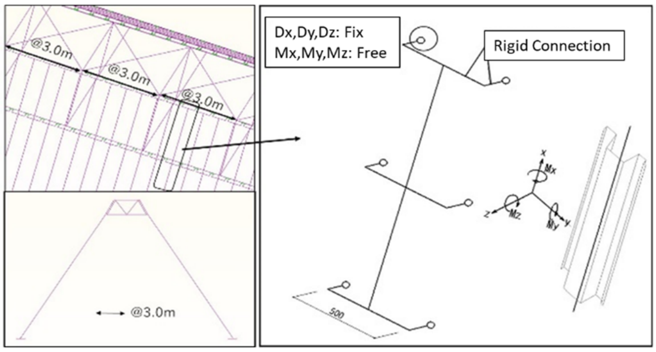


Fig. 7 Steel sheet pile connection conditions

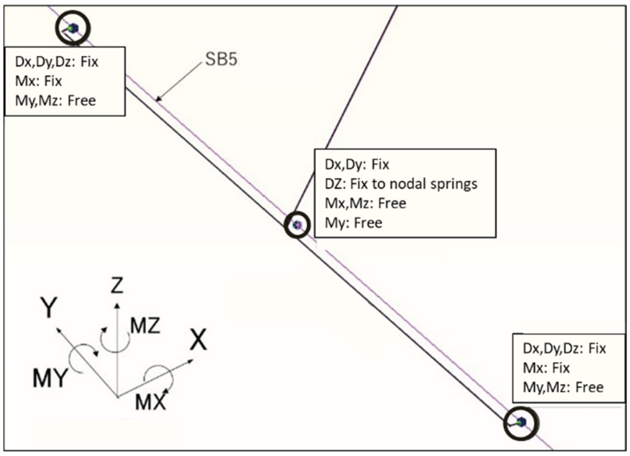


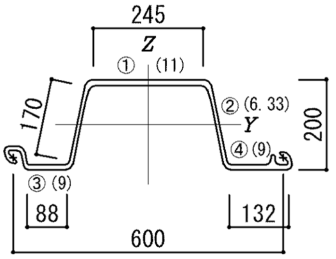
Fig.8 Boundary conditions

4. Discussion of Analysis Results

The slanted walls of this building are entirely composed of steel sheet piles. It has been confirmed that the basic cross-section of the steel sheet piles does not undergo local buckling up to the elastic limit strength, and that plane stability is maintained when subjected to bending in both the in-plane and out-of-plane directions. Since steel sheet piles are exposed to the external environment without finishing, 1 mm of rust on both sides shall be considered in the study.

4.1 Modeling of steel sheet pile

The width-to-thickness ratio was calculated in accordance with the allowable stress design criteria2) for steel structures, and it was confirmed that each section satisfied the limit value.



() values are thicknesses that take rusting into account

Fig. 9 Dimensions of sheet pile cross section

Table.3 Sheet pile width-to-thickness ratio

Parts	Plate size(mm)		width-thickness ratio	Limits	Judgment
	b	t	b/t		
①	245	11	22.27	≦ 42.2	OK
②	170	6.33	15.45	≦ 42.2	OK
③	88	9	8.00	≦ 13.9	OK
④	132	9	12.00	≦ 13.9	OK

4.2 Flatness retention of steel sheet piles

To confirm the retention of the sheet pile in-plane, a single sheet pile of 60cm width was taken out to compare the stiffness based on beam elements (wire model) and the stiffness based on plate elements (shell model) for in-plane and out-of-plane directional loading. The out-of-plane direction was confirmed by applying a central concentrated load (52.1 kN), which corresponds to the elastic limit capacity of the sheet pile, and the in-plane direction was confirmed by applying a horizontal force (20 kN) applied at the top of the roof section during a major earthquake. The sheet piles were examined with a length of 17.5 m at the bottom of the trapezoidal frame of the roof section.

(1) Out-of-plane directional force

The deformation at the center of the beam element model was 47.53cm, and 48.01cm for the plate element model (**Fig. 10**). Therefore, it can be concluded that the assumption of plane retention holds true for the out-of-plane applied force.

(2) In-plane directional force

The horizontal displacement at the top of the beam element model was 52.69cm, and in the plate element model it was 57.25cm (**Fig. 11**). The displacement of the plate element model was 1.09 times greater than that of the beam element model. Although the stiffness of the beam element model was evaluated higher than that of the plate element model, it is considered acceptable to use the beam element model because of the actual mating of the sheet piles.

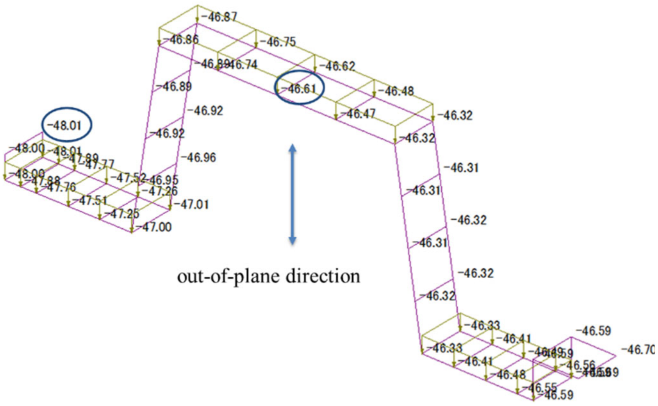


Fig. 10 Central deformation in out-of-plane direction(cm)

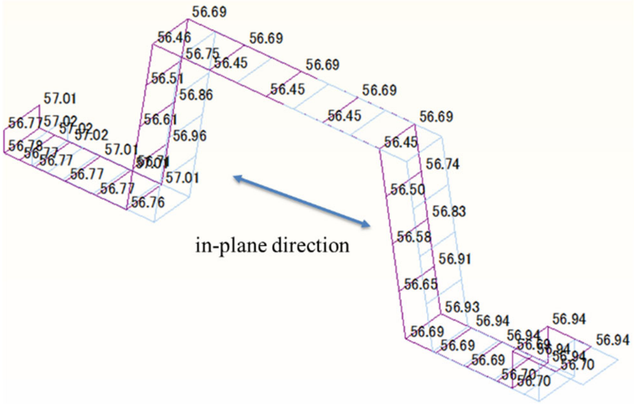


Fig. 11 Deformation of apex in in-plane direction(cm)

4.3 Temperature Stress Considerations

The foundation of this building is a direct foundation supported by steel plates buried in the ground. The sheet piles above ground are buried approximately 1 m underground as is. Since a temperature difference of up to 50 degrees Celsius can occur between the superstructure and the underground foundation, the safety of the connection of the column legs (SB5) was confirmed in consideration of the influence of the mating. Three types of flat bars were used to connect the sheet piles at 1 m pitch in the height direction in order to consider the connection of the sheet piles, and the following four cases were studied. **Fig. 12** shows the structural analysis model used for the temperature stress analysis.

Base model

Deformation in mating direction is not considered

Case 1

Connecting material PL-11×3@1000 (SS400)

Case-2

Connecting material PL-11×30@1000 (SS400)

Case-3

Connecting material PL-11×300@1000 (SS400)

As a result, maximum deformation occurred in case-1 and was 35.7 mm at the building legs and 26.1 mm at the top. The maximum axial force on the leg connecting members occurred in Case-3, with a value of 684.2 kN. The test value of SB5 ([-380 x 100 x 13 x 20 (SS400)]), the connecting member of the column legs, was 0.33, confirming that it was safe enough.

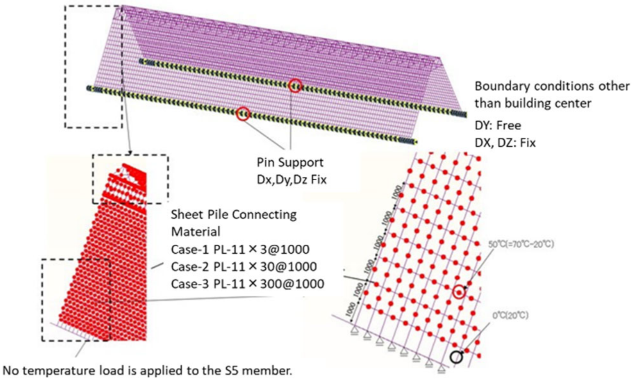


Fig. 12 Temperature loading conditions and connected parts

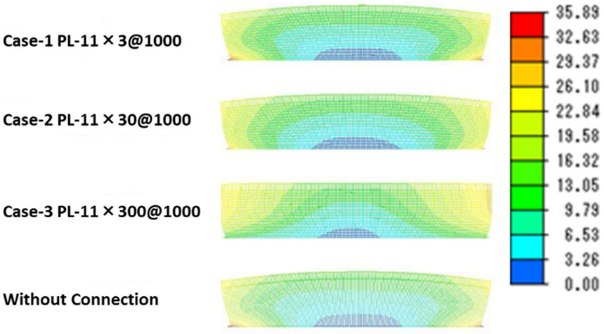


Fig. 13 Temperature loading conditions and connected parts

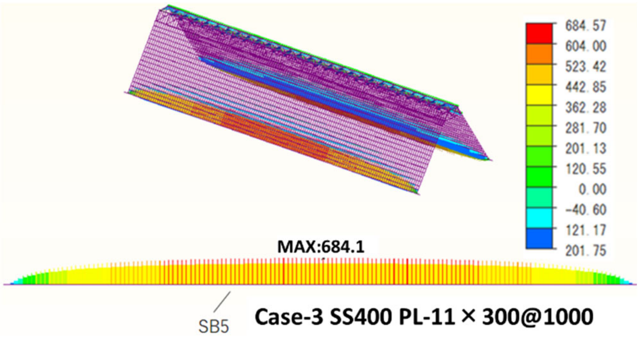


Fig. 14 Temperature loading conditions and connected parts

4.4 Results of Buckling Eigenvalue Analysis

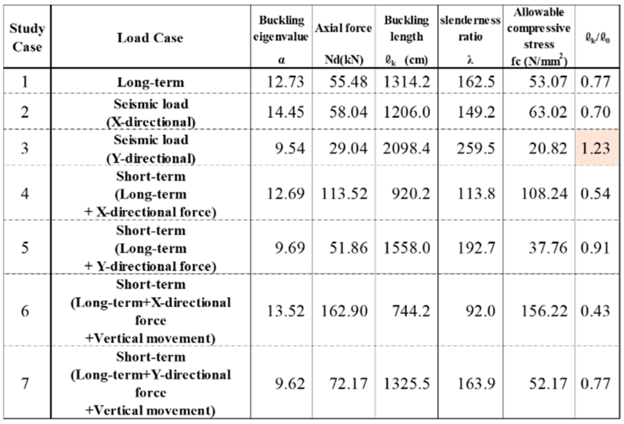
The components of this building are all steel sheet piles in the beam-to-beam direction, and all connections are pin structures. Buckling eigenvalue analysis was performed to calculate the allowable compressive stress of the diagonal walls in the beam-to-beam direction, and the buckling length of the steel sheet piles was calculated from the buckling eigen period α corresponding to the buckling mode and the design axial force N_d using the following formula.$^{3)}$

$$L_k = \pi \sqrt{\frac{EI}{\alpha \cdot N_d}}$$

EI: Bending stiffness of sheet pile
α: Buckling eigenvalue
Nd: Design axial force (kN)

The buckling lengths for each loading condition are shown in **Table 4**. Based on these results, the buckling length in the cross-sectional calculations was set to $1.23L_0$ only for the EY loading, and $1.0L_0$ for the other loading conditions.

Table. 4 Calculation results of buckling length



Study Case	Load Case	Buckling eigenvalue α	Axial force Nd(kN)	Buckling length ℓ_k (cm)	slenderness ratio λ	Allowable compressive stress fc (N/mm²)	ℓ_k/ℓ_0
1	Long-term	12.73	55.48	1314.2	162.5	53.07	0.77
2	Seismic load (X-directional)	14.45	58.04	1206.0	149.2	63.02	0.70
3	Seismic load (Y-directional)	9.54	29.04	2098.4	259.5	20.82	1.23
4	Short-term (Long-term + X-directional force)	12.69	113.52	920.2	113.8	108.24	0.54
5	Short-term (Long-term + Y-directional force)	9.69	51.86	1558.0	192.7	37.76	0.91
6	Short-term (Long-term+X-directional force +Vertical movement)	13.52	162.90	744.2	92.0	156.22	0.43
7	Short-term (Long-term+Y-directional force +Vertical movement)	9.62	72.17	1325.5	163.9	52.17	0.77

*) ℓ_0=1712.1cm

4.5 Confirmation of Retained Horizontal Bearing Capacity

Since this building is a one-story steel-frame structure, energy absorption by plasticity of the members cannot be expected. Therefore, Ds = 1.0 was assumed in the calculation of the necessary bearing capacity, and it was confirmed that stress in the members was less than the elastic limit bearing capacity. The inverse of the test value at that time was assumed to be equivalent to Qu/Qun, and the holding capacity Qu was calculated.

Qu/Qun = 1.27 when applied in X direction

Qu/Qun = 1.04 when applied in Y direction

Fig.15 and **16** shows the deformation diagrams. As a result, it was confirmed that the deformation angles were 1/79 in the X-direction and 1/78 in the Y-direction, which were within the limit of 1/75 for the exterior material to follow the deformation.

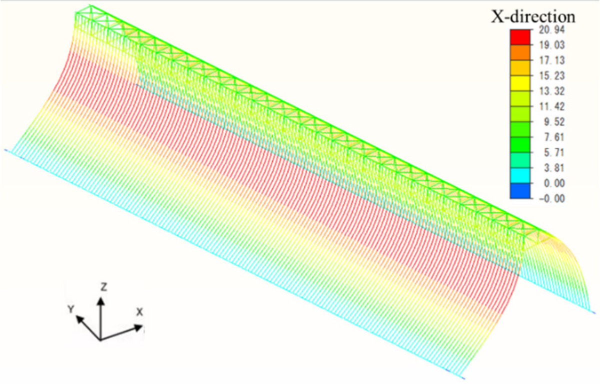


Fig. 15 Horizontal deformation X-directional force (cm)

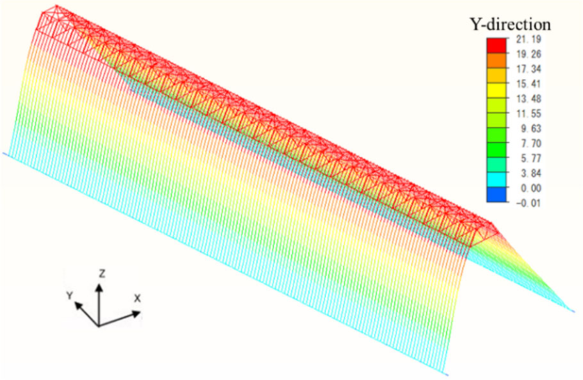


Fig. 16 Horizontal deformation Y-directional force (cm)

5. Construction Planning and Results

This chapter describes the construction procedure for this building.

5.1 Press-in of foundation steel sheet pile

First, 596 steel sheet piles to support the column leg steel sheet pile foundation, 46 steel sheet piles for the end wall, and steel sheet piles for the porch columns were pressed into the ground with SILENT PILER™ (**Fig. 17**). Then, the steel sheet pile foundations for the column legs were placed on macadam adjusted for compaction height, connected to the steel sheet piles with tie rods, and aligned horizontally (**Fig. 18**).

Fig. 17 Press-in of steel sheet pile

Fig. 18 Installation of column legs (steel foundation)

5.2. Construction of superstructure

Next, the upper trapezoidal frame was assembled (**Fig. 19**). The trapezoidal frame was supported by a scaffold that also served as a support structure, and a jack base was attached to the support of each upper frame to allow fine height adjustment. After the trapezoidal frames were installed, diagonal steel sheet piles near the beam joints were temporarily installed for safety to prevent them from tipping over. (**Fig. 20**) The main diagonal wall steel sheet piles were lifted up by two cranes at both ends, fitted with joints to match the angle of the diagonal wall, and slid into place. We applied lubricating oil to the joints to improve workability. We were able to install approximately 25 units per day (**Fig. 21**) Bolted joints at the top and bottom were made possible by precise position and height control of the steel sheet pile foundation and trapezoidal frame. The roof was then installed (**Fig. 22**) and the interior shoring was dismantled.

Fig. 19 Support scaffold assembly and trapezoidal frame installation

Fig. 20 Steel sheet pile construction on both sides of diagonal wall

Fig. 21 Installation of swale sheet piles

Fig. 22 Circular roof installation

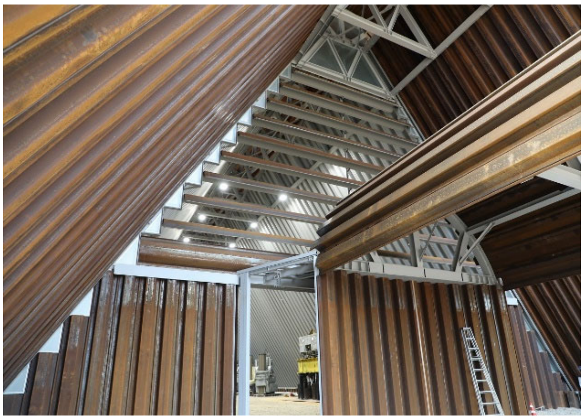


Fig. 23 Installation of louvers on end wall

Fig. 24 Porch section construction

Fig. 25 Interior finish

Fig. 26 Photo of completion

Fig. 27 **W**hole photo

6. Conclusion

The "Sozokan" is a warehouse that houses the SILENT PILER, which was recognized as a Mechanical Engineering Heritage by the Japan Society of Mechanical Engineers, as well as other inventions and developments of past generations. The main structural member (SM-J295) used for the building is a material used in piling material (of SIRENT PILER), which is mainly used in underground structures as an earth retaining wall. This time, the material was used as the main structural member to create a large-space structure. Taking into account the thermal impact on the interior due to the heat conduction of the steel outer walls, the internal environment is maintained favorable by incorporating a roof shape that allows air to escape at the top, and movable louvers constructed with sheet piles on the gable wall section. **(Fig. 23)** A two-story research building was also constructed on the site, using steel sheet piles as the main structural member. The building is used as a laboratory for various demonstration tests of press-in technology. Construction of this research building is also summarized in the another paper.

Acknowledgment

We express our heartfelt gratitude for the immense contribution of Mr. Kondo, a co-author and a structural engineer, to the success of this project and the completion of the paper.

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