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Sheet Pile Foundation and Design Method

Fondations en palplanches et dimensionnement

Spundwandgründungen und deren Bemessung

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1. INTRODUCTION

For the construction works in water cofferdam cells are generally needed so that they can be performed in the dry. In the design of cofferdam cells consideration must be given to the dimension of the area to be drained and to the head of water, earth pressure, waves, tides and so on, acting on the cells. For the purpose that the construction works in water can be done safely and economically, the sheet pile foundation method, described in this paper, has recently been developed and adopted widely in Japan. The characteristics of this method may be said as follows.

(1) The walled sheet pile foundation is built both as the main foundation structure and the temporary cofferdam cell. The cost and the period of construction by this method are less than by the ordinary methods.

(2) The flexural rigidity of this foundation can be expected to be similar to that of the caisson foundation, considering the shear resistance at joints & the rigid connection at footing in this foundation.

As the sheet pile foundation is considered to have lots of benefits in the construction works in water, in this way, it may greatly be noticed as a new type foundation.

2. CONSTRUCTION WORKS & STRUCTURAL CHARACTERISTICS OF THE SHEET PILE FOUNDATION

The sheet pile foundation was firstly adopted for a blast furnace foundation in 1965 and for the bridge foundation in 1969. The construction works by this method have become popular since that time and the total number of the works are about 150 for 40 bridges, for example, as of 1975. Table-1 shows the construction works of sheet pile foundation having large-dimensions. These sheet pile foundations become to be used in such large foundation structures as caisson foundations or large pile foundations. The sheet pile foundation is composed of steel pipe piles shown in Fig. 1, which are connected

Table 1 Construction works

name of bridge	date of start	basic dimensions		
		cross sectional dimensions of foundation	dimensions of steel pipe pile	number of foundation
		(mm)	ø x t xℓ(mm)	
Ishikari kako	1969. 6	8,877 x 20,483	812.8 x 16 x 42,000	2
Nanko renraku	1971.11	ø 15,210	1,219 x 13 x 33,000	3
"	1971.11	13,350 x 35,290	1,219 x 13 x 33,000	4
Shibatani heiya	1972.12	15,727 x 20,376	914.4 x 14 x 34,500	6
Minami huta renraku	1973. 2	22,225 x 15,008	1,200 x 14 x 28,000	2
Suehiro	1973. 3	ø 24,508	914.4 x 14 x 39,600	2
Ishikari	1973 5	ø 15,488	800 x 14 x 20,000	2
Shin Ebetsu	1973. 6	ø 15,506	800 x 16 x 27,000	3
Rokko island renraku	1973. 9	10,568 x 25,193	1,219.2 x 16 x 31,000	5
Shin Suigo	1973.11	26,445 x 16,186	1,219.2 x 19 x 57,500	4
Shin Kagasuno	1974. 3	ø 18,684	914.4 x 14 x 44,000	4
Senboku renraku	1974. 5	26,058 x 14,322	1,219.2 x 16 x 42.550	2

each other through joints and driven into bearing strata in a circular, oval or rectangular closed form as shown in Fig. 2. Since this foundation uses steel piles, it has such advantages that the construction works can be rationalized and completed within a comparatively short period of time, and that the penetraiton length can be chosen arbitrarily. In case of the caisson foundation, its cross sectional contour greatly influences the speed of the construction works. The constructing work of the sheet pile foundation, however, is little different from the conventional piling work, which is scarcely influenced on the work in spite of the size of the sectional contour.

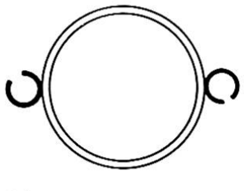

Fig. 1 Steel pipe pile

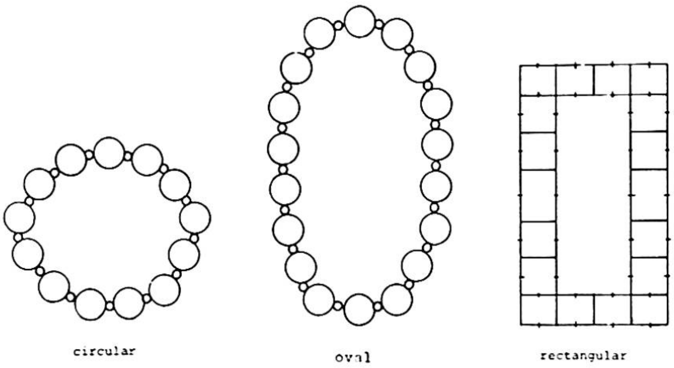

Fig. 2 Sectional forms

The sheet pile foundation has been developed as a sort of under-water construction method. It is divided into three types accroding to means of use, which are shown in Fig. 3. A is called the "Rising type foundation" of which the footing is above water surface. This type does not need a temporary cofferdam structure and its structure is similar to the multipile foundation. B is called the "Conventional type foundation" of which a closing wall is built independently on the foundation body. The temporary structure is the same to one of the conventional piling work in water. Its footing form is the same to one of A. C is called the "Cofferdam cells type foundation" of which the wall is used both as the main foundation body and the temporary structure concurrently. This is a unique type and has many remarkable merits. As a matter of fact, this C type foundation has adopted in most of sheet pile foundations already constructed. The design for the wall must be done by taking into consideration the hydraustatic and earth pressure for closure of the water in addition to design forces for the main structure. Fig. 4 shows several construction steps of this type.

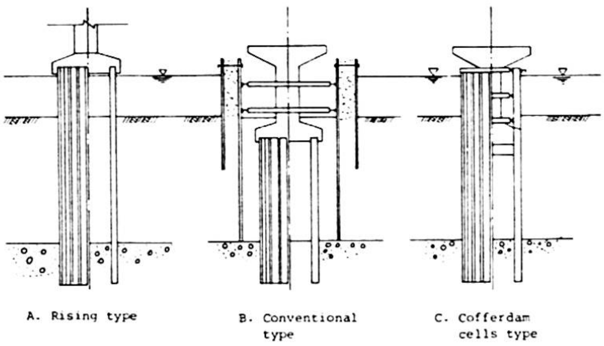

Fig. 3 Types of sheet pile foundation

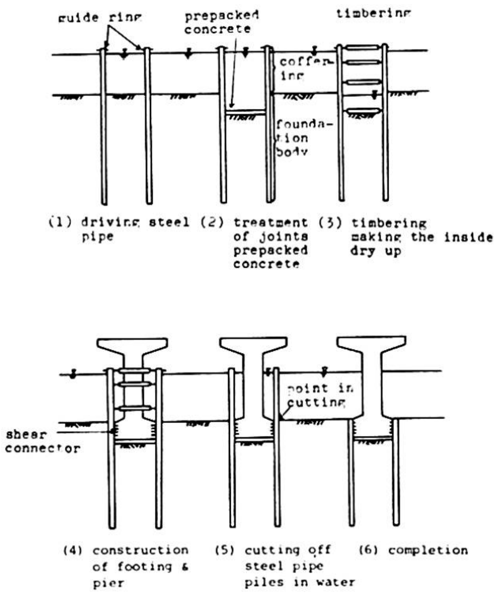

Fig. 4 Several steps in working "Cofferdam cells type"

The joints are generally treated by means of being filled with mortar in order to increase the flexural rigidity of the wall or to make water tight in case of the "Cofferdam cells type foundation". There are two kinds of the footing types. One is applied in the A type or the B type in Fig. 3. Its structure is the same to one of the conventional pile foundation. The other is used in the "Cofferdam cells type foundation" and is constructed inside the cylindrical wall. The connection between the wall and the footing is executed with shear plates and reinforced bars welded on sheet piles shown in Fig. 5.

3. EXISTING DESIGN METHOD

The "Guidance for Design and Construction of Sheet Pile Foundation" was proposed by Research Committee for Sheet Pile Foundation in January 1972. Its principal points are as follows. It is assumed that the sheet pile foundation is on an elastic media shown in Fig. 6. Its lateral resistance shall be calculated by the following formula.

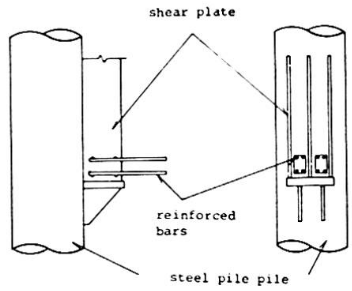

Fig. 5 Connection feature

$$\left.\begin{aligned} EIy^{(4)} + ky &= 0 \\ EI &= E\left\{[I_i] + \mu\,[A_i y_i^2]\right\} \end{aligned}\right\} \quad (1)$$

where, Ii : Moment of inertia of i-th pile
Ai : Sectional area of i-th sheet pile
Yi : Distance from center axis of foundation to one of i-th sheet pile

When the flexural rigidity EI is calculated, the effect is considered such that each sheet pile is composed of each joint and the footing. The EI value is evaluated by the composite efficiency μ. The coefficient μ ranges 0.0 to 1.0. In case of joints grouted with mortar, the μ is usually taken to be 0.5.

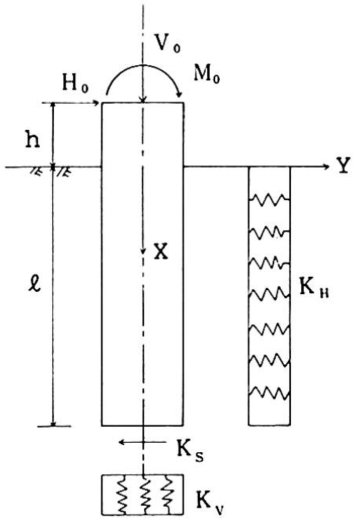

Fig. 6 Structural model

4. NUMERICAL ANALYSIS BY FINITE STRIP METHOD

For the purpose of analyzing theoretically the structural properties of the sheet pile foundation, a computer program by F.S.M. (Finite Strip Method) has been completed in which three-dimensional deformation of beam, shear deformation at joints and sectional deformation are considered. Following Assumptions are given for analysis.

(1) The circumference connecting centroids of each sheet pile is circular as shown in Fig. 7.
(2) The relationship between displacement of joint and shear force acting on it is proportional. This joint is also hinged on the section.
(3) Each sheet pile has no sectional deformation.
(4) The material of the ground is elastic.
(5) Ground conditions, shape of foundation and external forces are symmetrical to axis as shown in Fig. 7.

In case a supposed shell in Fig. 7 is considered, the central plane of this supposed shell coincides with the circumference of the cylindrical wall. It is assumed that the central axis of each sheet pile is connected with the central plane of this supposed shell and these have the same displacement. Considering the deformed section of the cylindrical wall at the central plane of the supposed shell, the section of the supposed shell is a continuous line, but one of the wall is hook-shaped as shown in Fig. 8.

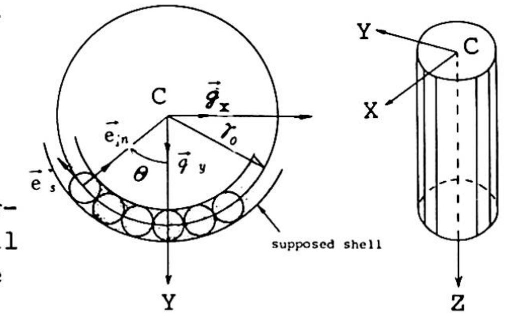

Fig. 7 Coordinate system

The unit vectors on the central plane of the supposed shell are shown in Fig. 7. The displacement vector U_0 in Fig. 9 on the central plane of the supposed shell is given by the unit vectors $(\vec{e}_s, \vec{e}_n, \vec{e}_z)$

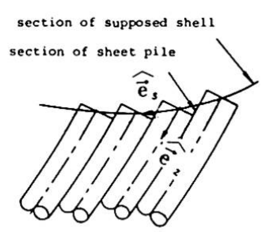

Fig. 8 Deformation of supposed shell and sheet pile

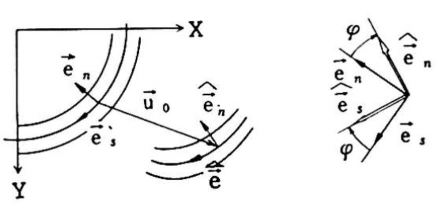

Fig. 9 Angular displacement of supposed shell

$$\vec{U}_0 = \xi_0 \vec{e}_s + \eta_0 \vec{e}_n + \zeta_0 \vec{e}_z \quad (2)$$

The angular displacement φ of the supposed shell in Fig. 9 is expressed by a finite series.

$$\varphi = \sum_{k=1}^{K} \left\{ \alpha_k(Z) \cdot \sin k\theta \right\} \quad (3)$$

where,

$$\theta = 0,\ \pi \ ;\ \varphi = 0$$

The shear strain $(\gamma xz)_0$ on the central plane of the supposed shell can be assumed as for a finite series by the beam theory.

$$(\gamma xz)_0 = \sum_{j=1}^{J} \left\{ \beta_j(Z) \cdot \sin j\theta \right\} \quad (4)$$

The coefficients of eq. (2) are obtained by eq. (3) and eq. (4).

$$\xi_0 = -Vc(Z) \cdot \sin\theta - \gamma_0 \sum_{k=2}^{K} \left\{ \alpha_k(Z) \cdot \frac{1}{k^2-1} \cdot \sin k\theta \right\} \quad (5a)$$

$$\eta_0 = -Wc(Z) \cdot \cos\theta - \gamma_0 \sum_{k=2}^{K} \left\{ \alpha_k(Z) \cdot \frac{k}{k^2-1} \cdot \cos k\theta \right\} \quad (5b)$$

$$\zeta_0 = -Wc(Z) \cdot \gamma_0 \cos\theta \cdot V\acute{c}(Z) - \gamma_0 \sum_{j=1}^{J} \left\{ \frac{1}{j} \cdot \cos j\theta \cdot \beta_j(Z) \right\} - \gamma_0^2 \sum_{k=2}^{K} \left\{ \frac{1}{k(k^2-1)} \cdot \cos k\theta \cdot \alpha_k'(Z) \right\} \quad (5c)$$

Getting displacements on the central plane of the supposed shell, displacement of each sheet pile and sliding displacements of joints are known. The displacement vector of a sheet pile, $\vec{U}$ is given as follows.

$$\vec{U} = U \cdot \vec{e}_s + V \cdot \vec{e}_n + W \cdot \vec{e}_z \quad (6)$$

$$U = \xi_0 - y \cdot \varphi, \quad V = \eta_0 + x \cdot \varphi, \quad W = W_0 - x \cdot \xi_0'(Z) - y \cdot \eta_0'(Z) \quad (7)$$

The sliding displacement of the i-th joint, $(\Delta W)_i$ is given as follows.

$$(\Delta W)i = -\gamma_0 \sum_{j=1}^{J} \left\{ (Aj)i \cdot Bj \right\} - \gamma_0^2 \sum_{k=2}^{K} \left\{ (Bk)i \cdot \alpha_k(Z) \right\} \quad (8)$$

where,

$$Aj = \frac{1}{j} \left(\left\{ \cos(j \cdot \Delta\theta) - 1 \right\} \cdot \cos j\theta - \sin(j \cdot \Delta\theta) \cdot \sin j\theta \right) \quad (9a)$$

$$Bk = \frac{1}{k(k^2-1)} \left(\left\{ \cos(k \cdot \Delta\theta) - 1 + \frac{b}{2\gamma_0} \cdot k \sin(k \cdot \Delta\theta) \right\} \cos k\theta - \left\{ \sin(k \cdot \Delta\theta) - \frac{b}{2\gamma_0} \cdot k \left\{ \cos(k \cdot \Delta\theta) + 1 \right\} \right\} \cdot \sin k\theta \right), \quad \Delta\theta = \theta_{i+1} - \theta_i \quad (9b)$$

Using the strains of a sheet pile obtained by eq. (6) and eq. (7), and the sliding displacement of a joint in eq. (8), the equilibrium equations and the boundary conditions are obtained by the principle of virtual works. These can be solved numerically. Once the part between the plane, Z = 0 and the plane, Z = ℓ in Fig. 7 is settled into a finite element, the displacement parameters Wc, Vc, α_k, β_j are expressed by suitable series which satisfy compatibility conditions.

$$\begin{aligned} Vc &= g_1 Vc^{(0)} + g_2 Vc^{(\ell)} + \ell \cdot g_3 \cdot Vc^{(0)\prime}(Z) + \ell \cdot g_4 \cdot Vc^{(\ell)\prime}(Z) \\ \alpha_k &= g_1 \alpha_k^{(0)} + g_2 \alpha_k^{(\ell)} + \ell \cdot g_3 \alpha_k^{(0)\prime}(Z) + \ell \cdot g_4 \cdot \alpha_k^{(\ell)\prime}(Z) \\ Wc &= \tilde{g}_1 Wc^{(0)} + \tilde{g}_2 Wc^{(\ell)}, \quad \beta_i = \tilde{g} \cdot \beta_i^{(0)} + \tilde{g}_2 \cdot \beta_i^{(\ell)} \end{aligned} \quad (10)$$

where,

$$\begin{aligned} &\tilde{g}_1 = 1-\mu, \ \tilde{g}_2 = \mu, \ g_1 = 1-3\mu^2+2\mu^3 \\ &g_2 = 3\mu^2-2\mu^3, \ g_3 = \mu-2\mu^2+\mu^3, \ g_4 = \mu^3-\mu^2, \ \mu = \frac{z}{\ell} \end{aligned} \quad (11)$$

By using the computer program based on the above-mentioned theory, local stresses of each sheet pile against a lateral force are principally investigated. Fig. 10 shows the model for calculation. Fig. 11 shows some of the results of the comparison between experimental stress distributions and theoretical ones. In Fig. 11, three theoretical values are shown. The theoretical value (1) is calculated under the conditions of the sliding rigidity of joints (120,000 t/m^2) and the ground model complied with Fig. 10, and the theoretical value (2) under ones of (60,000 t/m^2) and the ground model of the same to (1). The theoretical value (3) is calculated under ones of (120,000 t/m^2) and the lateral ground

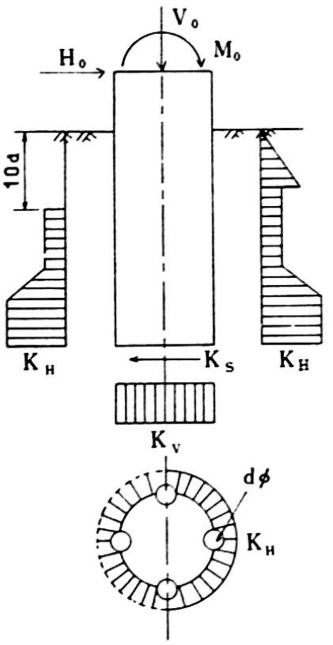

Fig. 10 Ground model

coefficient K_H which is constant regardless of the depth. In case the sliding rigidity of joints has lower value, there appear tendencies that the restraining stress near the footing becomes greater and that the maximum stress in the middle of ground decreases. Both of the theoretical values (1) and (2) are close to the experimental values as for the feature of stress distribution. There is, however, some difference between them as for the positions of local stresses. The theoretical value (3) catches the experimental values as a whole.

The notable local stresses both of the experimental and theoretical can be looked. The larger, the sheet pile foundation becomes, the more appears noticeable differences between each stress distribution by this F.S.M. and that by the existing method.

5. APPLICATION TO DESIGN

Principal points of the Guidance in Section 3 are described. In Section 4, the F.S.M. theory is shown which takes into consideration the relative displacement of each pile and the sectional deformation. When this theory is applied to real models, local stresses of sheet piles can be calculated reasonably. As it is concluded from the results that the mechanical properties of the structure can insufficiently be explained by the existing design method, more rational design methods should be substituted for the conventional ones.

Some of the studies for solving these subjects are briefly shown as follows. First of all, the simplest method is one added the eq. (1) to the term of shear deformation. Its basic formula is given as follows.

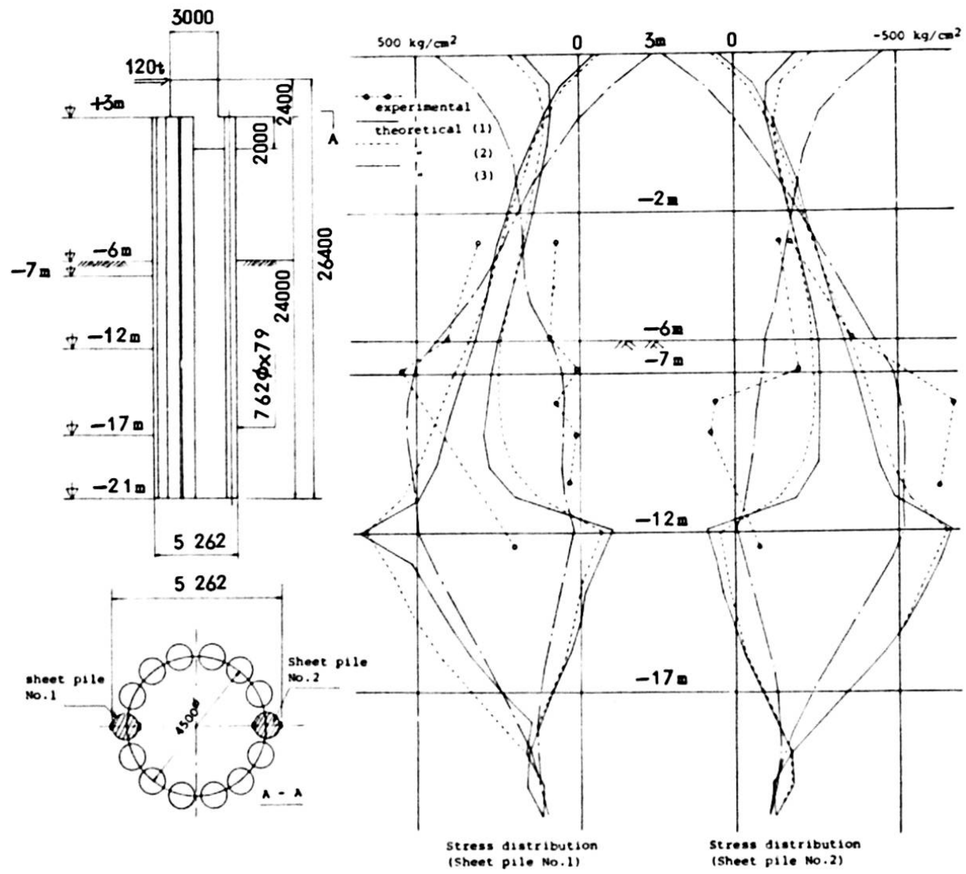

Fig. 11 Stress distribution

$$EIy^{(4)} - \frac{EI}{GA} \cdot ky^{(2)} + ky = 0 \qquad (12)$$

Considering the relative displacement in each joint, the basic formula is given as follows.

$$\frac{EI^*}{GA} \cdot EI_p y^{(6)} - E\,(I^* + I_p)\,y^{(4)} + \frac{EI^*}{GA} k y'' - ky = 0 \tag{13}$$

where,

$$EI = E\,[A_i y_i^2]\ , \quad EI_p = [I_i]$$

GA : Shearing rigidity   k : Spring constant of ground

It is impossible to obtain the general solution of eq. (12) and eq. (13). But eq. (12) or eq. (13) can be calculated by using a method like F.E.M.

Besides the mentioned methods above, a design of the sheet pile foundation can be made by using the design methods both of the pile foundation and the caisson foundation. The mechanical properties of the sheet pile foundation may be evaluated by the interpolation between their foundations. In case of this method, if the effect of shear transmission in joints is great, it is similar to the caisson foundation, and if in opposition, similar to the pile foundation.

Three methods above-mentioned and the conventional methods have equally both some merits and some demerits according to the size and the shape of the sheet pile foundation. Its design method should be investigated by means of the F.S.M. program shown in Section 4 and so on.

6. CONCLUSION

The sheet pile foundation has developed mainly as a method of construction works in water. It has so a wide range of dimensions that the existing method is not good enough to cover such an applicable range of designs. In this paper, its lateral resistance against earthquake forces is discussed. The program of F.S.M. shown in Section 4 is completed and hereafter its structural properties is analyzed. There is also another important subject which is the reliability of the rigid connection between the wall and the footing including the residual stress. Anyway, the sheet pile foundation has been used for about ten years, therefore, design standards should be established in the near future.

SUMMARY

The sheet pile foundation is a new type foundation. Structurally, this foundation differs conspicuously from the conventional types of deep pile foundation or caisson foundation. The process of development of the sheet pile foundation refers to the actual results obtained in its construction work, and its structural features. The design method in use is introduced and problems involved are analyzed. With a view to establish a rational design method, the structural features of the sheet pile foundation have been put to analysis in a computer program using the Finite Strip method. The theoretical background and part of the results of calculations are presented.

RESUME

La fondation en palplanches est un nouveau type de fondation. Elle présente des différences évidentes par rapport aux types existants de fondation profonde, telles que pieu ou caisson. Les exemples de travaux et les caractéristiques de la fondation en palplanches sont donnés. La méthode courante de calcul et certains problèmes sont évoqués. Une méthode de calcul pratique à l'ordinateur, tenant compte des caractéristiques structurales, est développée à l'aide de la méthode des bandes finies. La base théorique et une partie des résultats des calculs sont présentées.

ZUSAMMENFASSUNG

Die Spundwandgründung ist eine neuartige Gründungsform. Sie unterscheidet sich in konstruktiver Hinsicht wesentlich von den herkömmlichen Pfahl- und Senkkastengründungen. Die Entwicklung der Spundwandgründung, ihre Ausführung und ihre konstruktiven Eigenschaften werden aufgeführt. Dazu werden die zur Zeit eingesetzten Berechnungsverfahren dargelegt und die damit verbundenen Probleme erörtert. Die Berechnung dieser grosse Vorteile bietenden Konstruktionsart erfolgt elektronisch nach der Finite Strip Methode. Der theoretische Hintergrund und die wichtigsten Berechnungsergebnisse werden dargestellt.