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DESIGNING THE LARSSEN TYPE SHEET PILE SHAPE WITH THE INCREASED BEARING CAPACITY

O. Nosenko
PhD, Associate Professor
Department of Material Studies and processing of materials
State Higher Educational Establisbment «Pridneprovsk State Academy of Civil Engineering and Architecture»
Chernyshesky str., 24-a, Dnipro, Ukraine, 49005
E-mail: innes107@mail.ru

Стаття присвячена вдосконаленню профілів шпунтових паль типу Ларсен на підставі нової концепції проектування профілів, які працюють на вигин. Розроблено два профілі шпунтової палі підвищеної несучої здатності. Перший профіль Ларсен 7 (W=5010 см³) був розроблений і освоєний для умов його виробництва на рельсобалочному стані застарілої конструкції, а другий профіль шпунтової палі Ларсен 7Н (W=5200 см³) – для проектованого універсально-балочного стану

Ключові слова: сталевий шпунт, шпунтова паля, шпунтова стінка, несуча здатність,момент опору, профіль палі типу Ларсен, U-профіль

Статья посвящена совершенствованию профилей шпунтовых свай типа Ларсен на основании новой концепции проектирования профилей, работающих на изгиб. Разработаны два профиля шпунтовой сваи повышенной несущей способности. Первый профиль Ларсен 7 (W=5010 см³) был разработан и освоен для условий его производства на рельсобалочном стане устаревшей конструкции, а второй профиль шпунтовой сваи Ларсен 7Н (W=5200 см³) – для проектируемого универсально-балочного стана

Ключевые слова: стальной шпунт, шпунтовая свая, шпунтовая стенка, несущая способность, момент сопротивления, профиль сваи типа Ларсен, U-профиль

1. Introduction

Larssen type steel sheet piles, the most common in hydraulic engineering, are used in designs of sheet pile bulkheads at depths of up to 9.0...10.0 m. At greater depths, different shielding systems, multi-tiered anchoring, anchor attachment level lowering, backing filling, etc. are needed. This allows expanding the depth range for using the Larssen type steel sheet piles. However, this leads to a noticeable increase in the complexity and, ultimately, extends the terms and increases the cost of construction.

To meet the requirements of port hydraulic engineering in construction at depths of 15.0...25.0 m, especially in difficult engineering and geological conditions, and to effectively address the issues of reconstruction of hydraulic structures, it was necessary to use a steel sheet pile with increased bearing capacity in designs of sheet pile walls.

One of the effective ways to increase the bearing capacity of sheet pile walls is the development of new shapes of hot-rolled steel sheet piles with W>3200 cm³/m.sh.p.w. The solution to this problem is very urgent for Ukraine, especially after cessation of the manufacture of hot-rolled steel sheet piles and its promising renewal after commissioning of a new universal beam mill.

2. Literature review and problem statement

In the USSR, the manufacture of steel sheet piles has been launched at the rail and structural steel mill of the Dneprovsky Integrated Iron and Steel Works named after Dzerzhinsky (Dzerzhinsky DMK). Steel sheet piles provided the section modulus of one meter of a sheet pile wall (m.sh.p.w.) of W=2960 cm³ (Larssen-5) and W=2200 cm³ (Larssen-4). The annual output of shapes amounted to 160...200 thousand tons. Steel sheet piles were made of ordinary carbon steel with the yield point of 235...245 N/mm². Some batches of steel sheet piles were rolled of 16KHG low-alloy steel (yield point of 270...290 N/mm²). Larssen-5 and Larssen-4 steel sheet pile shapes, produced at the Dzerzhinsky DMK (Ukraine) have been excluded from foreign standards in 1984. Thus, steel sheet piles of the Dzerzhinsky DMK production in 1985 did not meet both the Euronorm standards and the requirements of modern hydraulic engineering.

The global level of hydraulic engineering is characterized by widespread use of steel sheet piles with W=3200 cm³/m.sh.p.w. (Larssen-5S). The increase in the bearing capacity of steel sheet piles was due to their manufacture of low-alloy high-strength steels (yield point of steel increased up to 400 N/mm²). The specific material consumption rate in foreign-made steel sheet piles is close to the standard value of 16 cm³/kg [1, 2].

The ranges of foreign-made sheet piles became much wider than those of domestic in terms of shapes and sizes, steel efficiency and steel grades used. Dimensional tolerances of sheet pile shapes in foreign standards became more stringent [1].

In North-West Europe, steel sheet piles are produced by the following companies:

– major steel-making group in France «USINOR-SACILOR» («UNIMETAL»);

– German company «Hoesch Stahl AG»;

– Luxembourg company «ARBED».

In Japan, steel sheet piles are manufactured by two companies, the leading of which is «KAWASAKI».

It is generally accepted that an increase in the reference values of bending shapes is achieved (on the example of an I-beam) by:

– increasing the distance from the axis of symmetry of the I-beam shape to extreme fibers of flanges;

– increasing the weight of the shape flanges, the farthest from the axis of symmetry;

– maximum possible thinning of the shape walls.

When improving the range of steel sheet piles in accordance with the above concept, the European standard developers had to come to the following conclusions:

1. There is no possibility of further increase in the shape height due to the achieved ultimate strength of rolls.

2. There is no possibility of any increase in the weight of the sheet pile shape wall since there is an objective regularity in the distribution of materials in the cross-sectional plane of the shape depending on the degree of thinning of the shape flanges.

3. The maximum possible thinning of the sheet pile flanges along the length of the flanges of the shape was made based on the conditions of stability for its driving into the ground.

Thus, in accordance with the above concept, the limit of improvement of sheet pile shapes – W=3200 cm^3/m.sh.p.w. has been achieved in the development of the European standard.

A further increase in the bearing capacity of sheet pile shapes was due to their manufacture of increased- or high-strength steels. The increase in the specific material consumption rate was due to the increase in the width of sheet piles between the Y–Y axes from 500 mm to 600 mm and 750 mm.

With regard to the achievement of limiting values of the section modulus of one meter of sheet pile wall, foreign researchers began to explore the strength margin of steel sheet piles under load. So, in [3], concern has been expressed regarding the resistance of U-shapes of steel sheet piles to bending loads. Reduction of the section modulus of one meter of sheet pile wall under the bending load has been also noted in [4]. In [5] the bearing capacity of sheet piles has been studied by two methods. The static load test has been conducted to determine the sheet pile resistance to bending load. Prediction of flexural strength of U-shapes of sheet piles under load has been carried out by numerical methods [6]. In [7] the rigidity of the sheet pile cross-shape has been investigated. The analysis included data of experimental studies and analytical modeling, aimed at determining the sheet pile wall resistance to strain.

Thus, experimental and analytical studies in the works [3–7] have revealed the reduction of the section modulus of one meter of sheet pile wall in connection with non-rigid interlocks of conjugated sheet piles. The results of the studies have also contributed to the development of amendments to the regulations and specifications. For example, the factors that provide accounting of assessment of the patterns of behavior of sheet piles under the bending load identified in the research were introduced in the recently adopted Eurocode 3 (Part 5). The proposed measures and recommendations fundamentally can not affect the operating conditions of the sheet pile wall under the bending load.

To increase the strength of the sheet pile wall and the rigidity of the cross-shape of the sheet pile shape substantially, a new sheet pile shape shall be designed. While maintaining the traditional U-shape of the sheet pile, a different distribution of the material in the cross-sectional plane of the shape is required. This will provide a solution to the problem of increasing the strength of one meter of the sheet pile wall (section modulus) and rigidity of the sheet pile cross-shape.

3. Goals and objectives

The goal of the research is to develop a shape of the Larssen sheet pile (U-shape) with increased bearing capacity (W>3200 cm^3/m.sh.p.w.).

The objective of the research is to develop a new design concept of the bending shape, providing the sheet pile shape with increased bearing capacity.

4. Materials and methods

The designed steel sheet pile with increased bearing capacity, as well as an analog (Larssen-5; W=2960 cm^3/m.sh.p.w.) were rolled of ordinary St3kp steel (GOST 380–...).

The methods used in the development of a new concept.

When developing a new design concept of steel sheet pile shapes, known [8] and newly proposed criteria characterizing the efficiency of cross-shape of bending shapes were used.

The research methods applied in the development of new steel sheet pile shapes.

During the development of the production technology of new sheet pile shapes with high bearing capacity, it was very important to determine the actual loads on the main mill line. This was due to the fact that the process of development of production of the new shape was held under limited technical capabilities of the rail and structural steel mill.

The studies were conducted on the rail and structural steel mill 925 of the Dneprovsky Integrated Iron and Steel Works named after Dzerzhinsky (Ukraine). The developed calibration (technology) was analyzed in the process of developing a new steel sheet pile shape by studying the forming of templates (samples) taken in the process of rolling of the first workpieces. The loads on the main drive motors and efforts perceived by rolls were studied by the rolling process oscillography.

In the study of the developed calibrations of sheet pile shapes, strain distribution in both passes, and the shape elements was analyzed. The analysis of these parameters was carried out theoretically both using the gage drawings, and the repeaters of templates (samples) taken when rolling the first test workpieces.

Measurements of the temperature of workpieces were performed with the OPPIR-09 optical pyrometer at two points along the cross shape (on the counter flange of the shape and the flange edge). Temperature measurement was carried out in the middle of the roll.

A study of the rolling speed, current loads on the main drive motors was carried out by interpretation of waveforms according to the readings of devices located on the control panels of mills and in the engine room. The numbers of revolutions of rolls at the time of entrance of pass and in the established process of rolling were determined. Monitoring was carried out throughout the course of steel sheet pile rolling.

The shaft torque of electric motors was determined theoretically by the formula:

$$M_m = 0{,}975 \cdot \frac{U \cdot I}{n} \eta, \qquad (1)$$

where M_m – motor shaft torque, t·m; 0.975 – correction conversion factor; U – voltage, V; I – maximum motor current, kA; n – motor shaft speed, rev/min; η – motor efficiency.

The torque was determined at the site of the motor acceleration to the rated speed (the first control zone). The values of electrical characteristics were taken from the waveforms. The values of torques were compared with the rated torques of the corresponding motor.

The equivalent current during groove rolling was determined in three ways. The first way was to the approximate the current line in the waveform by a broken line, which was divided into separate segments. Thus, the current waveform area was divided into simple figures – triangles, trapezoids and rectangles. In each of these areas, the equivalent current was determined by appropriate formulas. The second way was to determine the equivalent current by the graphical-analytical method: current ordinates were determined at regular intervals (0.1 sec), then the average current was determined as the arithmetic mean of the values obtained. The third method was to determine the areas of waveforms using a planimeter.

Investigation of the accuracy of the cross-sectional dimensions of finished rolled products was conducted by taking and measuring the samples of at least 300 mm in length. The samples were taken every 30 minutes throughout the course of sheet pile shape rolling and additionally after each adjustment of rolling mill stands. The weight of one meter of the shape was determined by calculation. Also, visual observation of the steel sheet pile shape surface was carried out.

The studies were performed when rolling the Larssen-5 sheet pile shapes (analog), and new Larsen-7A and Larsen-7 sheet pile shapes.

5. Development of a new design concept of sheet pile shapes with increased bearing capacity

The current design concept of bending shapes assumes (*on the example of an I-beam*) that efficiency of the shape is determined by the fact that:

– the shape flange material shall be as far as possible from its axis of symmetry X–X;

– the shape wall shall be as thin as possible (*in view of the shape stability*);

– distribution of the material in the cross-sectional plane of the shape shall be rational [8].

The new standards of cost-saving shapes (*UKRNIIMET, Ukraine*): GOST 8239–...(I-beams), GOST 8240–...(channels), GOST 8509–...(equal angle iron), etc. have been developed according to the above concept. The same has been done abroad in the development of standards for sheet pile shapes.

Fig. 1, 2 present the Larssen VI sheet pile shapes, designed in the 50s of the last century and the Larssen 5S sheet pile shape, designed in accordance with the new European standards. On the example of these two shapes, let us consider how the sheet pile shapes were improved when developing the European standards.

First, as can be seen in Fig. 1, 2, the height of the shapes is the same (250 mm). Larssen-5 sheet pile shapes were rolled at the Dzerzhinsky DMK. The height of the Larssen-5 shape was equal to 196 mm. The height of the Larsen-4 shape was 202.5 mm (*the shapes have been copied in the 50s of the last century from the French range of sheet piles*). The similar height of Larssen VI and Larssen 5S shapes only shows that it is a limit even for modern (*foreign*) rolling mills. In this case, it was not possible to increase it so that to increase the distance from the horizontal axis X–X of the sheet pile wall to the outer fibers of the sheet pile wall and thereby to increase the section modulus.

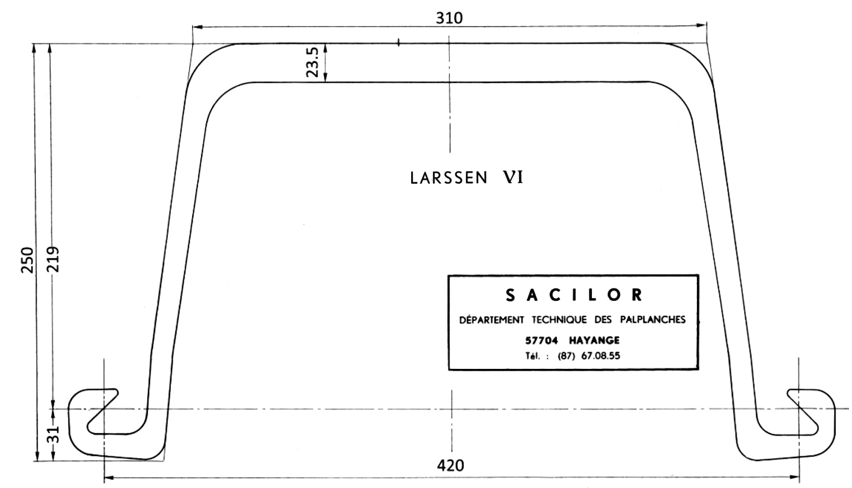

Fig. 1. Larssen VI sheet pile shape (W = 4200 cm^3.m.sh.p.w.)

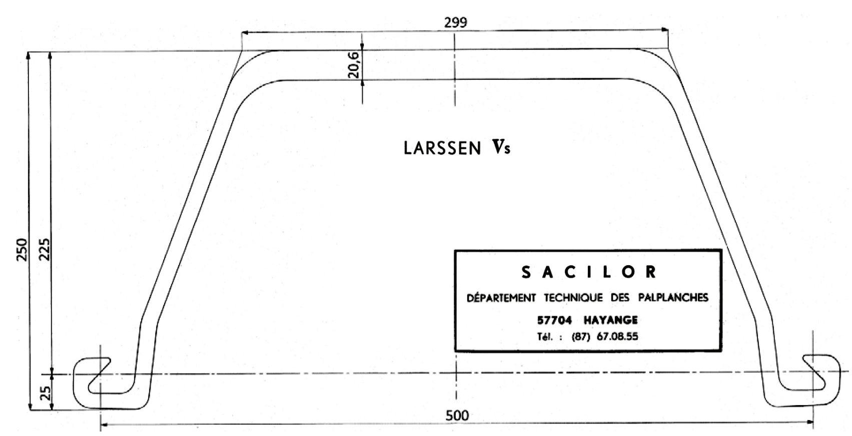

Fig. 2. Larssen 5S sheet pile shape (W = 3200 cm^3.m.sh.p.w.)

Second, as can be seen in the figures, the sheet pile width increased from 420 mm to 500 mm. Apart from the fact that an increase in the sheet pile width up to 500 mm simplifies the design process of hydraulic structures (*only two sheet piles rather than 2.38 account for a meter of berth when using the Larssen 5 sheet pile*), an increase in the sheet pile width leads to an increase in the specific material consumption rate. The latter is the most important economic indicator in selecting a shape for the sheet pile wall design. When comparing this index of the considered two shapes, it turns out that the specific material consumption rate in the Larssen 5S shape ($W=3200\ cm^3$/m.sh.p.w.) is higher than that of the Larssen VI shape ($W=4200\ cm^3$/m.sh.p.w.). These figures are respectively 15.09 and 14.48. Based on these indicators, the manufacture of the Larssen VI shape has been ceased and replaced with the Larssen 5S shape manufacture. The required bearing capacity ($N=\sigma_{0,2}\cdot W$) in the application of the Larssen 5S shape has been ensured by the use of increased or high strength steels. Such an example is the construction of the Amsterdam Schiphol Airport, where the Larssen 5S steel sheet pile made of high-strength E 430 steel has been used.

The third thing is different thicknesses of sheet pile flanges (*the I-beam wall matches the sheet pile flange in I-beams*). In the Larssen VI shape, the thickness of the flanges is 14 mm. In the Larssen 5S shape – 11 mm. Thinning of flanges in the Larssen 5S sheet pile shape has been caused by the desire to further increase the reference values of the sheet pile shape.

Thinning of sheet pile flanges is interconnected with the weight of the material concentrated in the sheet pile shape wall. This relationship is determined by the technological parameters of forming and deformation of the sheet pile shape workpieces in the rolling mill: the material of workpieces during rolling sheet pile shapes shall be distributed in the cross-sectional plane of the shape so that to ensure its straight passage out of gages of the rolling mill stand. The area ratio of the wall and flanges in the Larssen VI shape is 2.39. The same ratio in the Larssen 5S shape is 2.15. It is about the same, but even slightly lower, which should favorably affect the sheet pile shape production process.

It is generally accepted that an increase in the reference values of bending shapes is attained by:

– increasing the distance from the horizontal axis of the sheet pile wall;

– increasing the weight of the sheet pile wall, the shape element the most distant from the axis X–X of the sheet pile wall;

– maximum possible thinning of the sheet pile shape walls (based on the conditions of stability of the shape).

When considering the above directions for further improvement of the sheet pile shape, the development of the European standards revealed that:

– there is no possibility of further increase in the shape height – increase in the distance from the horizontal axis X–X of the sheet pile wall to the outer fibers of the sheet pile wall;

– there is no possibility of any increase in weight of the sheet pile shape wall, since there is an objective regularity in the distribution of material in the cross-sectional plane of the shape according to the degree of thinning of shape flanges.

The maximum possible thinning of sheet pile flanges along the length of shape flanges based on the condition of stability of shape when driven into the ground was performed (*the thickness of the shape flanges along the entire length is constant*).

Thus, according to a known concept described above and adopted within the European standard, it appeared that the limiting capabilities of improving the sheet piling shapes were achieved. A further increase in the bearing capacity of sheet pile shapes was to be achieved through their manufacture of steel with increased and high strength.

A new theoretical design concept of bending shapes was developed consisting in that:

– the design of shapes shall comply with the terms of rational distribution of the material in the cross-sectional plane of the shape;

– enhanced specific material consumption rate shall be ensured (W/G, cm^3/kg);

– the material concentration in the shape ($W/F\cdot h$) and shape efficiency ($W/F\cdot h x F_w/F_{fl}$) shall remain in the same range as that of the analog.

On the example of the Larssen 5S shape (analog), let us consider the possibility of a substantial increase in its reference values, using the new design concept of shapes.

Under the previous approach (*increasing the distance from the horizontal axis X-X of the sheet pile wall to extreme fibers of the sheet pile wall, increasing the shape wall weight and thinning of flanges*), the limit of capabilities in improving the sheet pile shape had been reached. When using a new concept, reference values of a new shape (*as compared with an analog*), including reference values of one meter of the sheet pile wall were significantly increased (1.7-fold).

The proposed concept is based on a new interpretation of the efficiency criteria of bending shapes:

– $\alpha_{rat}=\dfrac{F_w}{F_{sh}}$ – the criterion of the cross-section rationality of the shape;

– $\alpha_{conc}=\dfrac{W}{F\cdot h}$ – the criterion of the material concentration in the shape;

– $\alpha_{ef}=\dfrac{W}{F\cdot h}\cdot\dfrac{F_w}{F_{fl}}$ – efficiency criterion of the shape;

– $\dfrac{W}{G}\dfrac{cm^3}{kg}$ – specific material consumption rate in the shape.

6. Design of sheet pile shapes with high bearing capacity

At the same height (250 mm), the same width (500 mm) of the shape, in approximately the same area ratio of the wall and flanges, but with a different pattern of the material distribution in the cross-sectional plane, a new Larssen 7H sheet pile shape with high bearing capacity was designed. The section modulus of one meter of sheet pile wall – $W=5200\ cm^3$ (the patent of Ukraine No.109517) [9].

The section modulus of one meter of sheet pile wall of the analog shapes (Larssen 5S shape) – $W=3200\ cm^3$. Using the new concept, the Larssen 7 sheet pile shape with high bearing capacity – $W=5010\ cm^3$/m.sh.p.w.; $W/G=14.8\ cm^3$/kg (Fig. 3) was designed [10]. The analog was the Larssen-5 shape produced at the Dzerzhinsky DMK ($W=2960\ cm^3$/m.sh.p.w.; $W/G=12.4\ cm^3$/kg), and the Larssen 7H sheet pile shape ($W=5200\ cm^3$/m.sh.p.w.; $W/G=17.0\ cm^3$/kg) – on the projected new universal beam mill (Fig. 4).

It should be noted that the sheet pile shapes were designed under the conditions of their rolling on different mills: the Larssen-7 sheet pile shape – on the outdated rail and structural steel mill, the Larssen-7H sheet pile shape – on the projected new universal beam mill.

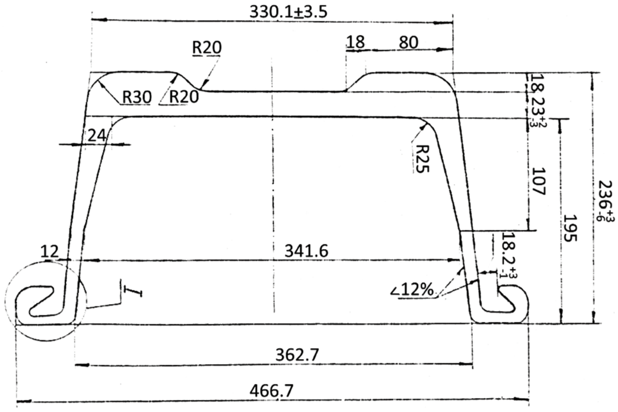

Fig. 3. Larssen-7 sheet pile shape

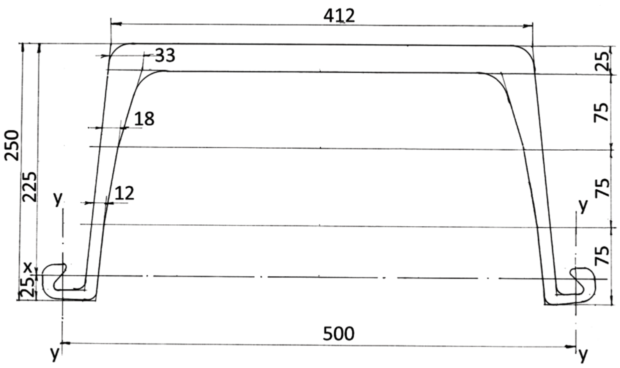

Fig. 4. Larssen-7H sheet pile shape

7. Conclusions

A new theoretical design concept of bending shapes was developed:

– the design of shapes shall comply with the terms of rational material distribution in the cross-sectional plane of the shape;

– an increase in the specific material consumption rate shall be ensured in the design of shapes (W/G, cm^3/kg);

– the material concentration in the shape (W/F·h) and the shape efficiency ($W/F \cdot h \cdot F_w/F_{fl}$) shall remain in the same range as those of the analogs.

The proposed new concept is based on a new interpretation of the efficiency criteria for the bending shapes:

– the criterion of the cross-section rationality of the shape – $\alpha_{rat} = \frac{F_w}{F_{sh}}$;

– the criterion of the material concentration in the shape – $\alpha_{conc} = \frac{W}{F \cdot h}$;

– efficiency criterion of the shape– $\alpha_{ef} = \frac{W}{F \cdot h} \cdot \frac{F_w}{F_{fl}}$;

– specific material consumption rate in the shape – $\frac{W}{G} \frac{cm^3}{kg}$.

It is shown that the Larssen-7H steel sheet pile shape (the patent of Ukraine for invention No. 109517), designed in compliance with the proposed new concept surpasses the Larssen-5S steel sheet pile shape, designed in compliance with the Euronorms in all respects. The application of these criteria, including the specific material consumption rate will allow both to objectively evaluate the characteristics of the existing shapes, and to develop new effective shapes.

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