Analysis of the lateral stability of the pile-driver SP-49

Rustam Khuziakhmetov\textsuperscript{1}\textsuperscript{[0000-0003-3737-018X]}, Rustem Sakhapov\textsuperscript{1}\textsuperscript{[0000-0001-9665-1251]}, Minsur Zemdikhanov\textsuperscript{1}\textsuperscript{[0000-0001-5207-2346]} and Svetlana Andreeva\textsuperscript{1}\textsuperscript{[0000-0003-0734-4618]}

\textsuperscript{1}Kazan State University of Architecture and Engineering, Kazan, Russia
E-mail: hroustam@mail.ru

Abstract. This study aims to exclude the possibility of pile driver capsizing due to exceeding slope of the construction site surface.

The paper determinates the reasons for the violation of the requirements of urban planning legislation and regulatory and technical documentation, which results in a pile driver capsizing.

The authors calculated the center of gravity of the pile driver and its lateral stability during the preparation of piles for driving and the driving itself.

The significance of the results for the construction industry lies in the need to increase the level of safety when performing pile work and taking into account the actual conditions of the site in the places of their implementation. At the investigated construction site, the slope of the construction site did not exceed a guaranteed safe value 3°.

Key words: pile driver, slope of the construction site, capsizing in the transverse plane, center of gravity.

1 Introduction

The safety of construction production in accordance with the Federal Law should be guaranteed throughout the life cycle of the building: engineering geological research, design, construction, including supervision and control during this period, operation. Construction phase should be accompanied by high-quality design documents, prepared construction site \cite{1-3}, proper construction mechanisms \cite{4-7}, ensuring construction and installation work with quality control and reliability of future operation of the facility. During operation, the technical condition of buildings should also be systematically monitored \cite{8-12}.

To carry out piling at this construction site, we used SP-49 pile driver. The study examined the problem of calculating the possibility of spontaneous lateral capsizing of the SP-49 when deviating from the passport requirements for the quality of preparation of the site on which the pile driving installation should work.

The construction industry has a high level of industrial injuries \cite{13-18}. However, nowadays the need for a professional approach to research, design, organization and the construction of facilities, and safety of all technological processes, is recognized widely \cite{19}.

The conditions of work were constrained due to the combination of various construction and installation works \cite{11, 12} and the saturation of construction machines and mechanisms at the zero-cycle stage. In addition, studies that go beyond the scope of this article have identified the other factors that contribute to the possibility of an incident:

- lack of sophistication in the design and estimate documentation of safety capabilities in the sections of the construction organization project and the production project;
- deviations from design decisions in the development of a two-stage excavation pit;
- violation of safety requirements during the implementation of work.
Based on this, we should note the urgent need to address security issues, starting with the stage of researching the conditions of a possible construction site in urban area with the development of technical solutions [19, 20].

In addition to exploring the possibility of pile driver capsizing, we assessed the condition of the excavation slope of the pit, which area was planned for piling, according to the construction organization project.

2 Materials and methods
In order to determine the possibility of the pile driver capsizing at the scene of the incident (figure 1), we studied its technical characteristics, the state of the soil of the construction site and the conditions for performing pile work. We also found that these works were carried out in cramped conditions (saturation with building mechanisms, combining work in adjacent areas).

![Figure 1. Photographs of the SP-49 at the scene.](image-url)
Inspection of the pile driver showed that as a result of the accident, mast structures, braces, and a hammer were damaged. The driver’s cab did not undergo significant deformations, except for some broken glasses. An external inspection didn’t detect any external damage to the chassis as well as to the controls (pedals, levers, dashboards) in the cab. When conducting an expert study, we looked at the regulatory and technical documentation for the used piling equipment, as well as information and technical materials for this equipment and the base machine. The main initial technical data for calculating stability are presented in table 1.

**Table 1. Summary of the calculations.**

| Indicator name                                      | Reference         |
|-----------------------------------------------------|-------------------|
| Base tractor                                        | T10MB             |
| Type of chassis                                     | Tracked           |
| Type of pile driver mechanism                       | Hydraulic         |
| Maximum length of driven pile, m                   | 12.0              |
| Maximum section of the driven pile, mm              | 350x350           |
| Maximum mass of driven pile, tons                  | 3.8               |
| Maximum load capacity, t, including                 |                   |
| on a rope for lifting a hammer                      | 12                |
| on a rope for lifting piles                         | 7.0               |
| Maximum allowable slope of the construction site   | 3º                |
| Track width, mm                                     | 2282±25           |
| Mast working tilts:                                 |                   |
| - right left                                        | 7º                |
| - forward                                           | 7º                |
| - back                                              | 18º               |
| Mast height change, m, not more than                | 0.4               |
| Weight of hinged part, without base machine and loader, tons, not more than | 8.7 |
| The maximum mass of the hammer with a headgear, tons | 6.0              |
| Mass of pile driver without hammer                  | 27.6              |
| Overall dimensions, mm                              |                   |
| - in working position                               |                   |
| Length                                              | 4830              |
| Width                                               | 5210              |
| Height                                              | 18510             |
| - in transport position                             |                   |
| Length                                              | 10710             |
| Height                                              | 4700              |
| Width                                               | 3540              |

Figure 2 shows the dimensions of the T10MB base tractor necessary for calculation. As a result of the calculation, it was necessary to determine (taking into account the removal of the mast to the left of the tractor to the maximum possible value of 0.4 m, as well as without the removal of the mast) two options:
- the center of gravity of the equipped pile driver;
- the angle of stability in the lateral plane of the equipped machine.
Figure 2. The dimensions of the tractor (a) and its center of gravity (b).

Figure 3 shows the coordinate system accepted for calculation:
- axis 0X is directed along the horizontal surface to the right;
- axis 0Y is directed upward along the axis of symmetry of the tractor;
- axis 0Z is directed from the plane of the picture.

On figure 3, the coordinates of the center of gravity of the mass of the tractor, the left side of the pile, the right side of the pile, hammer, pile and equipped pile driver are respectively indicated $O_1$, $O_2$, $O_3$, $O_4$, $O_5$ and $O_P$.

The coordinates of the center of gravity of the masses of the components of the equipped pile driver, as well as the summary calculation results are given in table 2.

Let’s consider the full weight of the equipped pile driver:

$$ m_{\text{full}} = m_{\text{trac}} + m_{\text{pop}} + m_{\text{ham}} + m_{\text{pil}}, $$

where $m_{\text{trac}}$, $m_{\text{pop}}$, $m_{\text{ham}}$, $m_{\text{pil}}$ — respectively, the mass of the tractor, poppethead, hammer and piles indicated in the table 2.
The total mass of the installation is determined based on the data in table 1: $m_{full} = 17300+8600+4700+3400=34000$ kg.

Let’s divide the poppethead mass into two parts. We bring the right part of the tractor $m_{trac.right}$ to the pulley block, and the right part $m_{trac.right}$ to the mast. Then:

$$m_{trac} = m_{trac.left} + m_{trac.right}$$  \hspace{1cm} (2)

We assume that $m_{trac.left} = 2000$ kg, $m_{trac.right} = 6600$ kg.

The distance between the external surfaces of the left and right tracks of the T-10MB tractor is $B = 3230$ mm.

1. We will determine all the required parameters taking into account the maximum extension of the mast to the left of the tractor along its movement by 0.4 m.

**Figure 3.** To the calculation of stability.
The masses and coordinates of the components of the pile driver, taking into account the removal of the mast by 0.4 m, are presented in table 2.

**Table 2.** Data for calculation taking into account the move of the mast on 0.4 m.

| Name                      | Mass \( m_i \), kg | GC Coordinates | Moments of force |
|---------------------------|-------------------|----------------|-----------------|
|                           | \( X_i \), m      | \( Y_i \), m   | \( m_i g X_i \),Nm | \( m_i g Y_i \),Nm |
| Tractor T-10MB            | 17300             | 0             | 0.81            | 0              | 137467          |
| Pile driver SP-49D:       |                   |               |                 |                |                 |
| - the right side          | 8600              | -             | -1.85           | -              | -36297          |
| - the left side           | 2000              | -1.85         | 2.59            | -              | 50816           |
| SP-7 Hammer               | 6600              | 1.62+0.4      | 7.2             | -              | 130787          |
|                           |                   |               |                 |                | 466171          |
| Pile 0.35×0.35×12000 m    | 4700              | 2.3+0.4       | 14.1            | 1               | 124489          |
|                           |                   |               |                 |                | 650109          |
| Poppethead combined with  | 34000             | 0.93          | 4.11            | 0              | 309035          |
| pile                      |                   |               |                 |                | 1370555         |

We find the sum of the moments of forces of the components of the equipped machine:

\[
\Sigma (m_i g X_i) = m_{\text{trac}} g X_{\text{trac}} + m_{\text{pop. right}} g X_{\text{pop. right}} + m_{\text{pop. left}} g X_{\text{pop. left}} + m_{\text{ham}} g X_{\text{ham}} + m_{\text{pil}} g X_{\text{pil}},
\]

(3)

\[
\Sigma (m_i g Y_i) = m_{\text{trac}} g Y_{\text{trac}} + m_{\text{pop. right}} g Y_{\text{pop. right}} + m_{\text{pop. left}} g Y_{\text{pop. left}} + m_{\text{ham}} g Y_{\text{ham}} + m_{\text{pil}} g Y_{\text{pil}}.
\]

(4)

where \( X \) and \( Y \) – absciss and ordinate of the corresponding forces, \( m \);

\( g \) – acceleration of gravity, \( \text{m/s}^2 \).

Substituting the values from the table 2, we get \( \Sigma (m_i g X_i) = 309035 \text{ Nm} \), \( \Sigma (m_i g Y_i) = 1370555 \text{ Nm} \).

We find the coordinates \( X_{\text{cen.gr}} \) and \( Y_{\text{cen.gr}} \) of gravity centres of the equipped machine with the pile. Knowing that \( \Sigma (m_i g X_{\text{full}}) = m_{\text{full}} g X_{\text{full}} \) and \( \Sigma (m_i g Y_{\text{full}}) = m_{\text{full}} g Y_{\text{full}} \), we can write:

\[
X_{\text{cen.gr}} = \frac{\sum m_i g X_i}{m_{\text{full}} g},
\]

(5)

\[
Y_{\text{cen.gr}} = \frac{\sum m_i g Y_i}{m_{\text{full}} g}.
\]

Substituting the values, we obtain:

\[
X_{\text{cen.gr}} = \frac{\sum m_i g X_i}{m_{\text{full}} g} = \frac{309035}{34000} = 0.93 \text{ m},
\]

(6)

\[
Y_{\text{cen.gr}} = \frac{\sum m_i g Y_i}{m_{\text{full}} g} = \frac{1370555}{34000} = 4.11 \text{ m}.
\]

(7)

Let’s define the lateral angle of stability (relative to the Z axis) of the equipped machine with a pile according to the formula Eq. (8):

\[
tg \alpha_0 = \frac{0.5 B - X_{\text{full}} l}{Y_{\text{full}}},
\]

(8)

where \( B \) – distance between the external surfaces of the left and right tracks, m.

Substituting the values, we obtain:

\[
tg \alpha_0 = \frac{0.5 \times 3.230 - 0.93}{4.11} = \frac{0.715}{4.11} \approx 0.167 \text{ or } \alpha_0 = 9.48^\circ.
\]

(9)

Thus, the limit angle of lateral stability at which the machine will tip over, taking into account the maximum extension of the mast to the left of the tractor along its movement by 0.4 m, is \( \alpha_0 = 9.48^\circ \).

2. We will determine all the required parameters without taking into account the extension of the mast to the left of the tractor in the direction of its movement, using the data in Table 3 - masses and coordinates of the components of the piling machine without taking into account the move of the mast are presented in table 3.

In this case
\[ X_{fill} = \frac{\sum m_i g X_i}{m_{fill}} = \frac{251352}{34000 \cdot 9.81} = 0.75 \text{ m}, \text{ and } Y_{fill} = 4.11 \text{ m} - \text{ has the same value as in the previous case.} \]

Then \( \tan \alpha_6 = \frac{0.5 \cdot 3.23}{0.75} = 0.865 \times \frac{0.21}{4.11} = 11.86^\circ. \)

**Table 3.** Data for calculation without taking into account the move of the mast.

| Name                        | Mass \( m_i, \text{ kg} \) | GC Coordinates | Moments of force |
|-----------------------------|-----------------------------|----------------|------------------|
| Tractor T-10MB              | 17300                       | 0              | 0                | 137467           |
| Pile driver SP-49D:         |                             |                |                  |
| - the right side            | 8600                        | -              | -                |                  |
| - the left side             | 2000                        | -1.85          | 2.59             | -36297           | 50816 |
| SP-7 Hammer                 | 6600                        | 1.62           | 7.2              | 104889           | 466171 |
| Pile 0.35×0.35×12000 m      | 3400                        | 2.3            | 14.1             | 106046           | 650109 |
| Poppetehead combined with pile | 34000                      | 0.93           | 4.11             | 251352           | 137055 |

In this case \( X_{fill} = \frac{\sum m_i g X_i}{m_{fill}} = \frac{251352}{34000 \cdot 9.81} = 0.75 \text{ m}, \text{ and } Y_{fill} = 4.11 - \text{ has the same value as in the previous case.} \)

Then \( \tan \alpha_6 = \frac{0.5 \cdot 3.23}{0.75} = 0.865 \times \frac{0.21}{4.11} = 11.86^\circ. \)

### 3 Results

The calculation of the center of gravity of the equipped pile driving machine SP49D based on the T-10MB tractor with a pile with a cross section of 0.35 × 0.35 m and a length of 12 m showed:

1. The horizontal coordinate of the center of gravity of the equipped machine is offset from the vertical axis of symmetry of the tractor to the right by 0.93 m with a maximum mast extension from the tractor by 0.4 m and 0.75 m without the move of the mast from the tractor. The vertical coordinate of the center of gravity of the equipped pile driver is 4.11 m.

2. The limit angle of lateral stability at which the machine can tip over, taking into account the maximum extension of the mast to the left of the tractor along the course of its movement by 0.4 m, is equal to \( \alpha_6 = 9.48^\circ \), and without the removal of the mast \( \alpha_6 = 11.86^\circ \).

### 4 Discussion

The fall of a loaded pile driver in the lateral direction towards the mast is possible if the slope of the construction site is exceeded:

- more than 9.48° when moving 400 mm along the mast console with a pile;
- more than 11.86° without removal of the mast with pile on the console.

The pile driver manual states that on the site when driving piles with the SP-49, the slope of the construction site should not exceed 3°. In real conditions, at the construction site when driving piles there was no slope of the soil surface by more than 3°.

![Figure 4. Construction site slope angles.](image-url)
The slope of the construction site by no more than 3° indicated in the operation manual, is guaranteed to be safe even while driving in the lateral direction. For visualization, figure 4 shows various angles of slope to the horizontal.

The analysis of the developed design documentation and the photographs taken at the scene of the incident showed that the construction site does not have a slope exceeding 3°.

5 Conclusions
The study of the state of the construction site, engineering and geological conditions, as well as the calculation of the center of gravity of the equipped pile driving machine SP-49 based on the T-10MB tractor with a pile with a cross section of 0.35 × 0.35 m and a length of 12 m showed that:

1. The slope of the soil surface of the construction site does not exceed the safe value (3°) specified in the operating manual.
2. The slope of the soil surface of the construction site could not be the reason for the lateral capsizing of the pile driver and its fall.
3. The fall of a loaded pile driver in the lateral direction towards the mast is only possible if the slope of the construction site is exceeded;
   - more than 9.48° when moving 400 mm along the mast console with a pile;
   - more than 11.86° without removal of the mast with pile on the console.
4. The fall of the pile driver into the pit occurred as a result of the loss of stability of the slope of the pit when driving piles in the immediate vicinity of the edge of the slope.

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