Software and Hardware System for Fast Processes Study When Preparing Foundation Beds of Oil and Gas Facilities

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Abstract. Analysis of existing technologies for preparing foundation beds of oil and gas buildings and structures has revealed the lack of reasoned recommendations on the selection of rational technical and technological parameters of compaction. To study the nature of the dynamics of fast processes during compaction of foundation beds of oil and gas facilities, a specialized software and hardware system was developed. The method of calculating the basic technical parameters of the equipment for recording fast processes is presented, as well as the algorithm for processing the experimental data. The performed preliminary studies confirmed the accuracy of the decisions made and the calculations performed.

1. Introduction

The expansion of existing and development of green fields located at considerable distance from the places of material and technical supply, in the complicated engineering, geological and climatic conditions, actualizes the development of existing and search for new technical and technological solutions in the design, construction and operation of oil and gas buildings and structures [1-4]. Analysis of the current normative documentation [5-6], regulating technical and technological approaches in the design and maintenance of buildings and structures foundation beds showed the lack of adequate technologies that meet modern challenges. Currently, this work is underway aimed at solving a complex problem, as the rational use of materials and mineral resources, the reduction of planned facilities commissioning terms while ensuring the stability and reliability of this new unit during its lifetime. An example of such modern approach to solving this complex problem is the development of technology for direct compaction. The technology idea consists in forming a field of vertical compressive stresses of required spatial configuration in the soil half-space [7-8], thus a reduction is expected to be achieved in installed power requirements for the rammer equipment used compared with the currently used. It is obvious that the study of the specific interaction dynamics of building machine working bodies and foundation beds will determine both as rational technical as rational technological parameters of the buildings and constructions bases of oil and gas in difficult geological and climatic conditions. The specific recommendations availability for the selection of rational parameters would reduce material and time costs for the foundation beds preparation for oil and gas facilities.
In the course of analytical studies earlier performed, dependencies that describe the dynamics of the rammer element working body in the foundation bed of a vertical steel tank for oil storage were obtained [9]. To assess the obtained ratios accuracy, it was decided on simulating the interaction of the rammer mechanism working body and disconnected particulate soil, typical for clay base of the tank for storing oil under laboratory conditions. As a rule, most speed and displacement sensors are the contact type and introduce an additional disturbing effect on the measurement results. Therefore, the decisive factor in choosing the method for recording the process under study was the condition to minimize the influence of the recording device. Modern photo-video and computer technology development level allows remote, contactless nature of such measurements. The main advantage of recording with high-speed photo and video shooting is the ability to visualize fast processes, contactless and remotely data receiving in the most informative form, namely - photo and video. The absence of any influence on the process under study excludes the introduction of additional errors in the data obtained. It is important for an accurate and unambiguous interpretation of the objects under study dynamics. Furthermore, the complex use of photo-, video- and computing simplifies and accelerates both recording and subsequent processing of the results [10].

To make laboratory research of the construction machines working bodies’ influence dynamics on the foundation bed, a specialized software and hardware system was developed, including a laboratory stand, recording equipment and a software product for video frames processing.

2. Laboratory bench

To determine the laboratory bench dimensions it is necessary to know the nature and magnitude of the vertical compressive stresses spatial distribution from the acting external dynamic load in the soil. In the course of laboratory research, models made of steel with mass up to 0.3 kg were used as ramming machine working bodies. The models planned impact rate on the soil half-space should not exceed 1.7 m/s. The lack of unambiguous and reliable data on the spatial distribution of vertical compressive stresses in the ground, resulting from impact on the ground, facilitated the adoption of two assumptions. Due to the small masses and impact velocities, it is proposed: to use the model of spatial distribution of vertical compressive stresses for the static load case, to limit the considered area of vertical compressive stresses distribution with area 10 % of the stress from the actual load. In accordance with accepted assumptions, the dimensions of the bench will be determined with the magnitude of the vertical compressive stresses spatial distribution area which is 10 % of the acting load:

\[
\begin{align*}
H_{st} & \geq 4k_iH \\
B_{st} & \geq 6k_iH
\end{align*}
\]

where \(H_{st}\) is the bench width, m; \(B_{st}\) is the bench height, m; \(H\) is the linear dimension of the model in a direction perpendicular to the direction of its movement, m; \(k_i\) is impact coefficient considering the dynamic nature of the soil loading (assumed to be one).

Thus, in accordance with (1) a box construction with width \(H_{st} = 0.7\) m and height \(B_{st} = 0.75\) m was selected as a bench for laboratory research (figure 1 A).

3. Recording equipment

The recording equipment for conducting laboratory studies includes: a high-speed video camera (1), a control computer (2) and an uninterruptible power supply (3) (figure 2 B).

Initially, to select the required technical characteristics of the recording equipment, it is necessary to determine the speed of the process under study recording and its duration, which is provided with technical capabilities of the fastest video camera itself. For existing machines and mechanisms, as well as technologies used for the foundation bed compaction of typical buildings and structures, according to various sources, the duration of the soil compacting process as a rule is in the range from 10...95 ms [11-13]. At the same time, the researchers do not give unambiguous recommendations on the necessary
number of shots and time discreteness between them for qualitative and quantitative assessment of the model impact on the ground.

**Figure 1.** Laboratory bench (A); recording equipment (B).

It was decided to use high-speed video, providing process under study recording with discreteness between the frames taken an order less than its duration. That is, to study the dynamics of the model in the ground, it is proposed to perform high-speed video shooting with duration of at least ten frames. In this case, the temporal discreteness between individual frames should not exceed 0.001 s. Such temporal discreteness between frames corresponds to a shooting frequency 1000 frame/s. These requirements correspond to the high-speed video camera TMC-6740GE with maximum shooting frequency 1250 frame/s (figure 2 B), thereby fully meeting the terms of time resolution.

In turn, the recording equipment required spatial resolution is determined with characteristics of the speed camera lens and the relative spatial position of the recording equipment and the area under study. The angular resolution of the high-speed video camera photosensitive element cannot be considered, as it is much higher in most modern cameras than angular resolution of the used regular lenses. If a specific video lenses model has been selected than condition for obtaining high-quality images of the object allows specifying the requirements for the mutual spatial position of the recording equipment and the study area. This requirement observance shall be ensured with the corresponding depth of field (DOF) $\Delta p$. DOF $\Delta p$ is the distance along the optical axis of the shooting lens, within its limits the objects located are displayed on the photosensitive element with a sufficient sharpness degree. Since the recording of the model impact on the ground is supposed to be carried out from a distance that excludes damage to the lens and video camera with ground particles and ensures the minimum vibrational impact on the study, the DOF value $\Delta p$ is proposed to be calculated with formula [14]:

$$\Delta p = \frac{2l_{obs} \cdot d_{perm}}{D \cdot f}.$$  \hspace{1cm} (2)

where $l_{obs}$ is observation distance from the camera lens front surface to the subject, m; $d_{perm}$ is the value of the permissible confusion diameter circle, m; $D$ is diameter of the entrance pupil, m; $f'$ is back focal length of the lens, m. Obviously, formula (2) also allows to select the necessary objective lens for the given requirements to the spatial resolution of the researches and/or the relative spatial position of the recording equipment and the area under study.

In the experimental studies, sandy soil of medium size with an average particle size 0.38 mm was used. Recording of soil particles movement under the influence of an external force was intended to
perform up to \( d_{\text{perm}} = 0.1 \) mm. The DOF value was assumed equal to the maximum longitudinal (along the axis of the lens) size of the rammer mechanism working body \( \Delta p = 45 \) mm. Using lens Navitar DO-5095, having focal length \( f' = 50 \) mm, f-number \( K_r = 0.95 \ldots 16 \) and the angular field in the space of objects \( 2\omega (H \times V) = 14^\circ 36' \times 11^\circ 00' \), allowed to calculate the technical parameters of the shooting. The minimum f-number corresponds to the fully open aperture; the maximum value corresponds to the fully closed aperture. The maximum observation distance for the extreme f-number will be:

\[
\left\{ \begin{array}{l}
 l_{\max}^{\text{obs}} (K_e = 0.95) = \frac{\Delta p \cdot f'^2}{2 \cdot d_{\text{perm}} \cdot K_e} = \sqrt{\frac{45 \cdot 50^2}{2 \cdot 0.1 \cdot 0.95}} \approx 770 \text{mm} = 0.77 \text{m} \\
 l_{\max}^{\text{obs}} (K_e = 16) = \frac{\Delta p \cdot f'^2}{2 \cdot d_{\text{perm}} \cdot K_e} = \sqrt{\frac{45 \cdot 50^2}{2 \cdot 0.1 \cdot 16}} \approx 190 \text{mm} = 0.19 \text{m}
\end{array} \right.
\]

The linear dimensions of the observation field in horizontal \( H_r \) and vertical planes \( V_r \) for the extreme f-number \( K_r \) will be:

- for \( K_r = 0.95 \):
  \[
  \left\{ \begin{array}{l}
  H_r = 2 l_{\text{obs}} \arctan \frac{\omega H}{2} = 2 \cdot 0.77 \cdot \tan 7^\circ 18' \approx 0.197 \text{m} \\
  V_r = 2 l_{\text{obs}} \arctan \frac{\omega V}{2} = 2 \cdot 0.77 \cdot \tan 5^\circ 30' \approx 0.148 \text{m}
  \end{array} \right.
  \]

- for \( K_r = 16 \):
  \[
  \left\{ \begin{array}{l}
  H_r = 2 l_{\text{obs}} \arctan \frac{\omega H}{2} = 2 \cdot 0.19 \cdot \tan 7^\circ 18' \approx 0.049 \text{m} \\
  V_r = 2 l_{\text{obs}} \arctan \frac{\omega V}{2} = 2 \cdot 0.19 \cdot \tan 5^\circ 30' \approx 0.037 \text{m}
  \end{array} \right.
  \]

The maximum size of the model in the plane under study is \( L = 65 \) mm. Angular field of the selected lens in the object space in a vertical plane equals to \( 2\omega (V) = 11^\circ 00' \). Thus, the maximum f-number \( K_r \) of the lens in the planned laboratory tests will be:

\[
K_r = \frac{2 \Delta p \tan^2 \omega f'^2}{L^2 d_{\text{perm}}} = \frac{2 \cdot 45 \cdot \tan^2 5^\circ 30' \cdot 50^2}{65^2 \cdot 0.1} \approx 4.9
\]

4. **Software product for processing video frames**

Special software (SS) "Single-frame analyzer" was designed to handle high-speed frame video footage to obtain data on the objects dynamics (figure 2).

The following requirements have been presented to the developed SS:

- automatic loading of SS video frames with time reference depending on the shooting speed;
- determination of the image true scale;
- the possibility of scaling the video frame;
- ability to determine the current values of both the linear displacement and the speed of a given point of the object, and its vertical and horizontal components;
- possibility of changing the frame exposure rate during its processing.
Figure 2. SS working window "Single-frame analyzer".

The process of video frames processing consists of two stages: the preparatory stage and the stage of the frame processing (figure 3).

Figure 3. The sequence of processing video frames.

The preparatory stage is intended for setting parameters for viewing and processing high-speed video shooting. The first step in the preparatory stage is to set the viewing scale of the video frames. This step reduces the effect of the screen pixel resolution the frames are viewed on to the processing results. The next step is to load the first frame of high-speed video. For the SS operation all the shooting is to be sequentially numbered. Since the high-speed TMC-6740GE video camera used in the laboratory studies sequentially numbered each video frame, then at this step the frame with the smallest number in the series is loaded.
After downloading the frame number is displayed on the SS working panel in the "Source Viewer" and "Current Frame" windows. Simultaneously for this frame, the current video time is set to zero, and it is also displayed on the SS working panel above the frame itself (figure 2). In the case of the standard frame size, the SS automatically detects the video speed and displays its value in the "Rate of shooting" field. In addition, it is possible to enter manually the value of the shooting speed in this field. The value of the video speed allows calculating automatically the current time of each frame uploaded. For correct calculation of the moving and speed values of the analyzed object, in the fourth step of the preparatory stage, the scale of the displayed image is determined. To do this, two points must be marked in the field of the exposed frame; the distance between them is 1 cm vertically on the real object. The setting of the frames exposure rate is performed in the fifth stage. Entered in the field "Frame scan duration" number allows to set the time convenient for processing the automatic change of the captured video frames. At the final stage of the preparatory phase, the analysis mode is set: constant or discrete. Constant analysis mode allows monitoring sequentially the dynamics of one selected point, determining its movement and speed by consecutive clicks on each analyzed frame. Discrete mode allows monitoring the dynamics of different points on every two consecutive frames.

At the stage of processing frames, the dynamics of the objects under study are analyzed directly. Frame processing begins with the time reference of the loaded frame. The time reference of the frame is calculated by the frame number in the series. Clicks on the point chosen for analyzing the dynamics on each subsequent frame allow calculating the speed and movement of the point from frame to frame. At the next processing stage, the calculated data is displayed automatically in the SS lower left corner. To ease the analysis calculated numerical values are represented as orthogonal components (horizontal and vertical components of the displacement and speed), as linear values. At the end of the set exposure time of the current frame, the next frame is loaded automatically, and the processing of the loaded frame is resumed. After processing of the last video frame is completed, the first frame is automatically loaded, the time counter is reset and the initial repetition of the stage of the video frames selected series processing is possible.

5. Discussion of the results

In preliminary laboratory studies the designed hardware and software system was tested during the motion study under the influence of the gravitational force of the metal cone (figure 4 A) and water drops (figure 4 B).

![Figure 4](image)

**Figure 4.** Video frames of the fall of the conical model (A) and the formation of a splash of water (B).

Video processing of free fall and subsequent impact of the conical model on sandy ground via SS "Single-frame analyzer" allowed to determine the nature of the model velocity change over time (figure 5). The preliminary data allowed identifying in the dynamics of the conical portion two characteristic parts: section I "Acceleration" and section II "Breaking". The interface portions is shown
with dashed red line in Fig. 5. Section I "Acceleration" is characterized with a constant increase in the speed of the model. It is noteworthy that the duration exceeds the available models fall under the gravitational force. Sometime after the contact with ground the model continues the accelerated motion. The beginning of the model impact on the ground is marked with a blue line. Section II "Breaking" is characterized with a sharp decrease in the speed of the model with its maximum value to zero.

![Figure 5. The model speed change during the free fall and the subsequent impact on the ground.](image)

The preliminary data also made possible to give an evaluation characteristic of the integral precision of the hardware and software system and the proposed methods for studying fast processes in the preparation of foundation beds of oil and gas facilities.

Linear approximation of discrete data to changes in the model free fall speed until the hit into the sandy ground has allowed to establish a functional dependency of model change speed under gravitational force and compare it with the known one (figure 6).

![Figure 6. Change in velocity of the model free fall.](image)
The calculated value of the acceleration relative error of free fall via the used techniques of data recording and processing was 0.4%. In view of the stochastic nature of the physical and mechanical properties of sandy soil the result obtained is satisfactory.

6. Conclusions
In accordance with the proposed methodology there has been developed software and hardware system for studying rapid processes in the preparation of foundation beds of oil and gas facilities. The layout scheme and dimensional characteristics of the laboratory bench were defined. A high-speed video camera, controlled by PC was used as recording equipment. Specialized software product “Single-frame analyzer” was designed to handle video. Equipment used and program product enable fast processes recording with time increments up to 1 ms, with spatial discreteness up to 0.1 mm. The relative error in determining the dynamic characteristics of the processes under study using the methods for recording and processing data is 0.4%.

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