

# Improving the dependability of light vented foundations exposed to vibration load on frost soils

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**Abstract. Aim.** Today, dynamically-loaded foundations of process equipment often prove to be oversized with significantly overestimated values of stiffness, mass and material consumption. Therefore, reducing the costs and time of construction of gas pipeline facilities, especially on permafrost, is of relevance to PJSC Gazprom. One of the primary ways of solving this problem is installing gas pumping equipment on light vented support structures. The disadvantage of such structures is the low vibration rigidity. A method [1] is proposed for improving the vibration rigidity of a foundation subjected to vibration load. The simulation aims to improve the dependability of light vented foundations by studying vibration displacements of foundations with attached reinforced concrete panels depending on the thermal state of frost soils, parameters of the attached panels and connectors. **Methods.** Vibration displacements of a foundation with an attached device were identified using the finite element method and the improved computational model of the foundation – GCU – soil system. **Results.** Computational experiments identified the vibration displacements of the foundation in the cold and warm seasons for the following cases of reinforced concrete plates attached to the foundation: symmetrical and non-symmetrical; at different distances; through connectors with different stiffness parameters; with additional weights; frozen to the ground. **Conclusions** were made based on the results of simulation of vibration displacements of foundations with an attached device in cold and warm seasons. **Conclusion.** The presented results of computational experiments aimed at improving the vibration rigidity of light foundations by using method [1] show sufficiently good indicators of reduced vibration displacements of the foundation. Thus, in the case of symmetrical connection of four reinforced concrete panels in summer, the reduction of vibration displacements is 42.4%, while increased stiffness of the connectors, attachment of additional weights and freezing of reinforced concrete panels into the ground will allow reducing the vibration displacements of the foundation up to 2.5 times. However, it should be noted, that applying the findings in the process of development of project documentation and construction of foundations requires R&D activities involving verification and comparison of the obtained results of numerical simulation with a natural experiment.

**Keywords:** reduction of vibration displacements, GCU foundation, dynamic load, connector, weight.

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## 1. Introduction

Today, dynamically-loaded foundations of process equipment often prove to be oversized with significantly overestimated values of stiffness, mass and material consumption. Therefore, reducing the costs and time of construction of gas pipeline facilities, especially on permafrost, is of relevance to PJSC Gazprom. One of the possible solutions consists in installing gas pumping equipment on light vented support structures. The disadvantage of such structures is the low vibration rigidity, which is compensated by a massive reinforced concrete panel on top of the foundation, increased number and depth of pile penetration, which causes longer time of foundation construction and material consumption. Improved vibration rigidity of light support structures is made possible by the “Method for improving the dynamic stiffness of foundations exposed to vibration load and the device for its implementation” [1] (hereinafter referred to as the Method).

## 2. The Method

The Method involves the attachment of an additional structure to the foundation through connectors for the purpose of transferring dynamic loads from the foundation to the soil. That reduces the vibration displacements of the foundation, which saves costs associated with the vibration protection of foundations with minimal earthwork. As the additional structure, the paper considered the attachment of reinforced concrete panels (hereinafter referred to as RC panels) for transferring dynamic loads from the foundation to the soil (see Fig. 1). That reduces the vibration displacements of the foundation, thus saving costs associated with vibration protection of the foundation with minimal earthwork. Additionally, the installation of RC panels on the surface of the soil without penetration minimizes the problems of frost soil thawing in the course of operation.

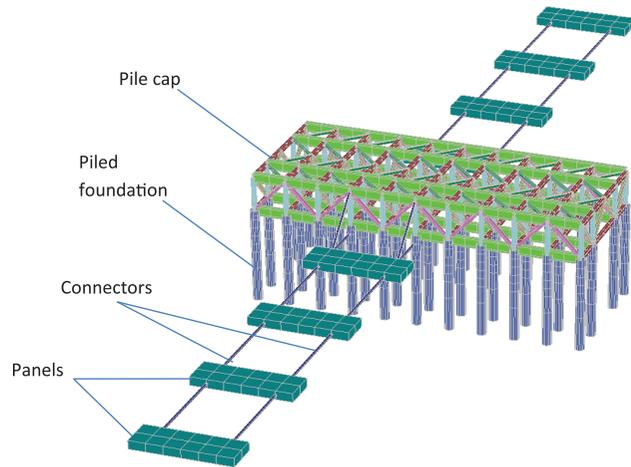


Fig. 1. Diagram of reinforced concrete panels attached to a foundation

The following measures are foreseen for the purpose of maximizing the effect of the Method: weighting of the attached RC panels and ground freezing, as well as selection of parameters (stiffness, dimensions, placement) of the connectors and the attached RC panels for transferring elastic oscillatory waves into the soil mass.

A number of computational models were developed for the purpose of identifying vibration displacements of the foundation of a 25 MW “Ural” gas compressor unit (GCU) caused by dynamic loads using the example of frost-bound soil. Frost-bound soil is characterized by the fact that the layer that thaws over the summer completely freezes over the cold season, thus forming a single frozen mass. The vibration displacements of the foundation were identified using an improved computational model of the underlying soil [2, 3]. Data for calculating the dynamic load caused by the rotation of the rotors of GPA-25 Ural are given in Table 1. For the purpose of demonstrating the simulation results, the eccentricity of the rotors, based on test data, is conventionally taken as

Table 1. Data for dynamic load identification

| Name of moving part                           | Mass, kg | Rate of rotation |                  | Centrifugal force, N |
|---|----------|------------------|------------------|----------------------|
|   |          | n, rpm           | $\omega$ , rad/s |                      |
| Power turbine (PT) rotor, $m_3$               | 670      | 5250             | 550              | 314                  |
|   |          | 5000             | 523              | 284                  |
|   |          | 3500             | 366              | 139                  |
| Low pressure turbine (LPT) rotor, $m_1$       | 753      | 4600             | 481              | 270                  |
|   |          | 4300             | 450              | 236                  |
|   |          | 3200             | 335              | 131                  |
| High pressure compressor (HPC) rotor, $m_2$   | 410      | 12000            | 1256             | 1003                 |
|   |          | 11670            | 1221             | 947                  |
|   |          | 10150            | 1062             | 717                  |
| Transmission of gas turbine power unit, $m_4$ | 160      | 5250             | 550              | 75                   |
|   |          | 5000             | 523              | 68                   |
|   |          | 3500             | 366              | 33                   |
| Compressor rotor, $m_5$                       | 1350     | 5250             | 550              | 633                  |
|   |          | 5000             | 523              | 572                  |
|   |          | 3500             | 366              | 280                  |

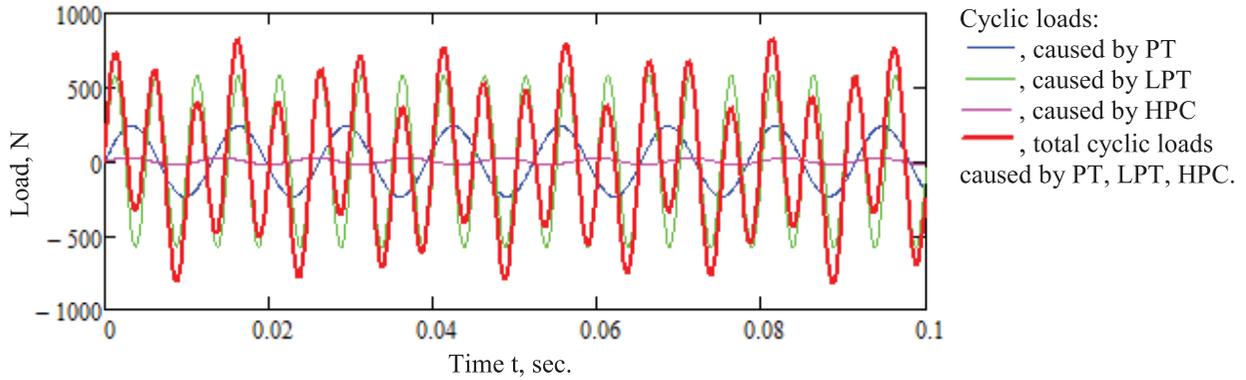


Fig. 2. Graphs of the intermittent loads affecting the engine support

$e = 1.5 \mu\text{m}$  or  $0.0015 \text{ mm}$ . This parameter depends on the precision of rotor manufacture.

A simultaneous exposure of a foundation to rotors rotating at different speeds is a polyharmonic force [4], (see Fig. 2). The total vibration amplitude is found by adding component vibration displacements from each source individually.

$$\sum_{i=1}^n y_i = A_1 \sin(\omega_1 t + \delta_1) + A_2 \sin(\omega_2 t + \delta_2) + A_3 \sin(\omega_3 t + \delta_3) + A_4 \sin(\omega_4 t + \delta_4) + A_5 \sin(\omega_5 t + \delta_5) \quad (1)$$

where  $A_1, A_2 \dots A_5$  are the vibration amplitudes caused by intermittent loads  $R_1, R_2 \dots R_5$ ;  $\delta_1, \delta_2 \dots \delta_5$  are phase angles;  $\omega_1, \omega_2 \dots \omega_5$  are angular frequencies of the sources of intermittent loads.

Obtaining the results of the computational experiment only requires defining one of the components of the vibration displacement of the foundation, e.g., the one caused by the intermittent load  $P_3 \cdot \sin(\omega_3 \cdot t)$ , where  $P_3 = m_3 \cdot e_3 \cdot \omega_3^2$  is the dynamic load due to the rotation of the power turbine's rotor, H [5],  $\omega_3$  is the cycle frequency of the rotor's rotation,  $1/s$ ,  $t$  is the time, s.

The vibration displacements were determined for the warmest and the coldest times of the year for the following cases, respectively:

- I. Symmetrical and non-symmetrical attachment of RC panels;
- II. RC panel attached 5.25 m to 23.25 m away from the foundation's centre line;
- III. Attachment of RC panels through connectors with the stiffness ratio  $K$  ranging from  $175560 \cdot 10^3$  to

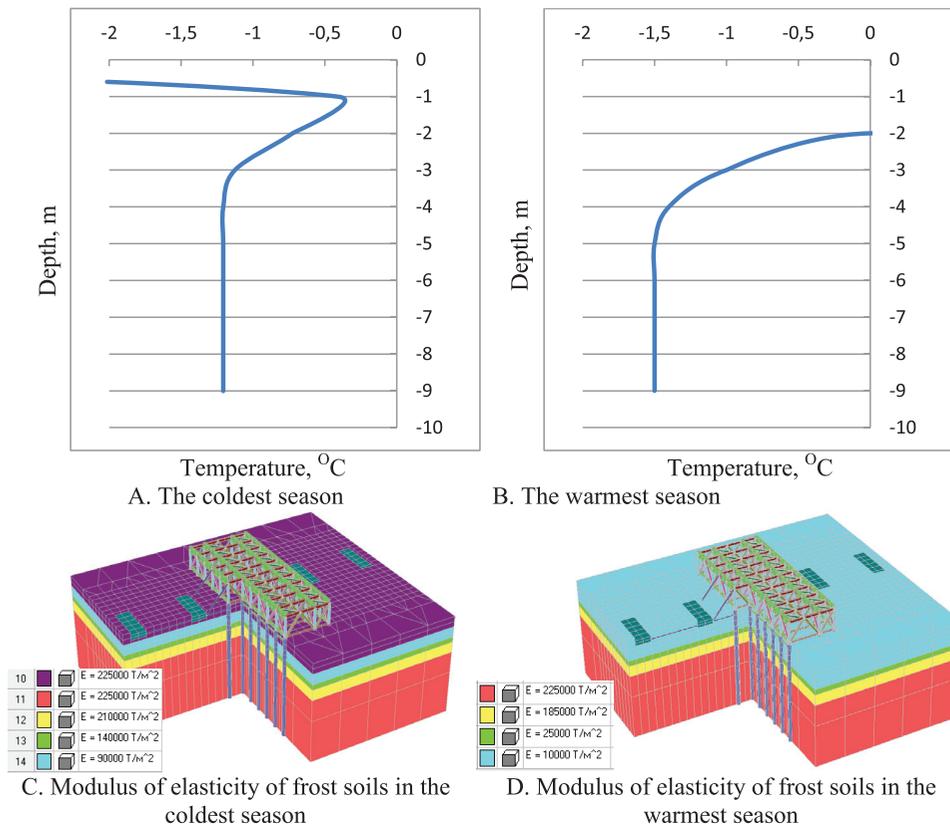


Fig. 3. Distribution of temperatures and elastic moduli of frost soils throughout the depth of the underlying soil

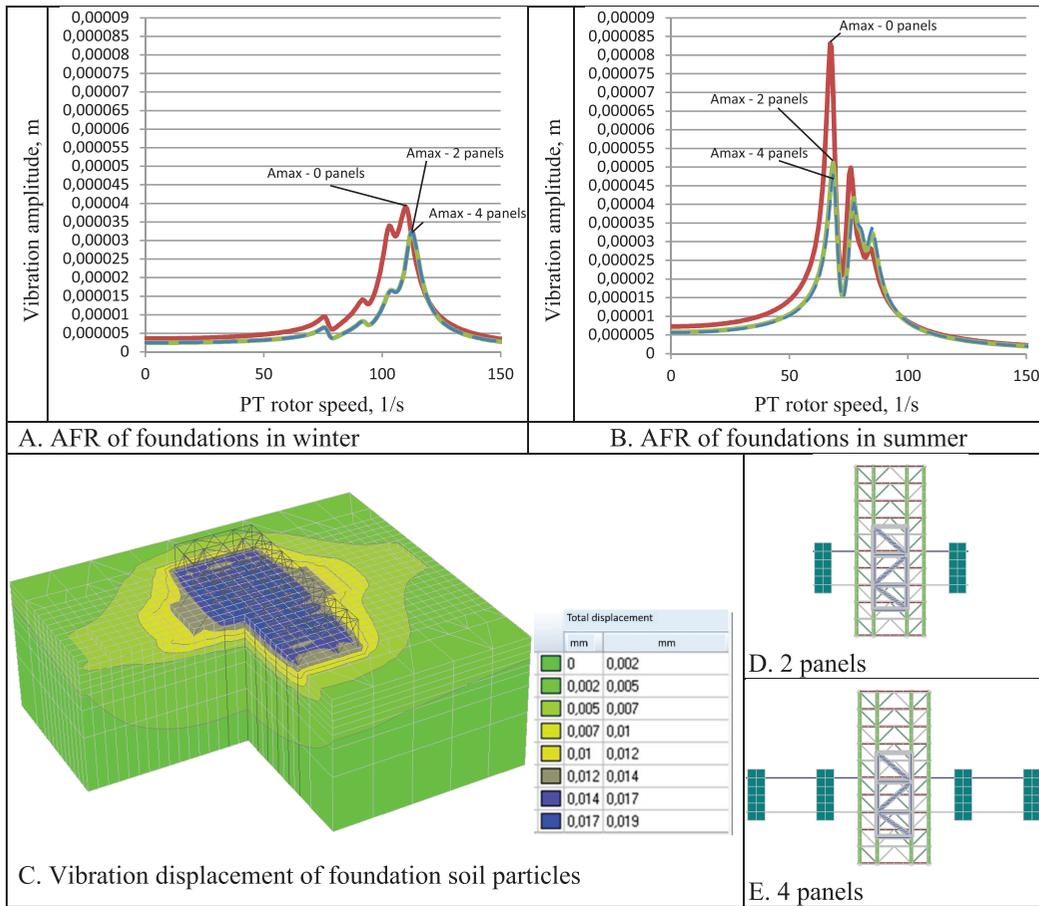


Fig. 4. Definition of vibration amplitude of foundations with symmetrically attached RC panels

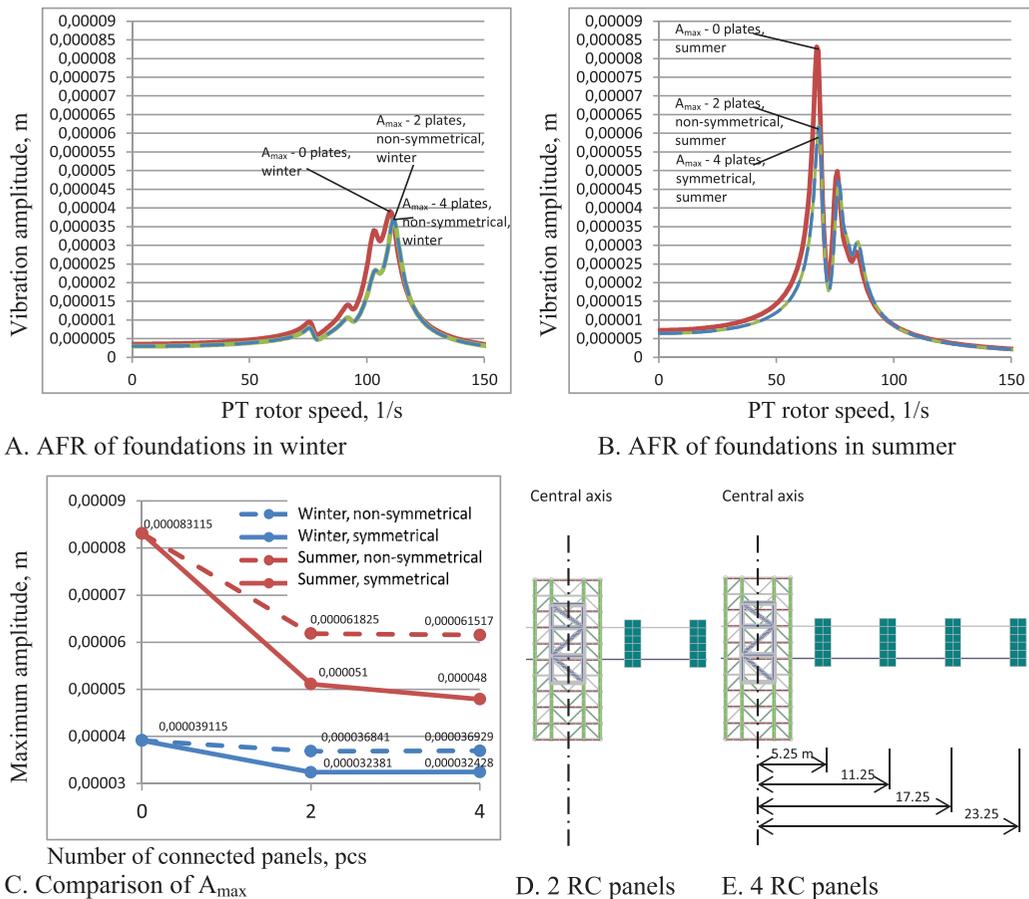


Fig. 5. Comparison of the AFRs of foundations with non-symmetrically attached RC panels

$2251200 \cdot 10^3 (H \cdot M^2)/M^2$ , where  $K = E \cdot S$ ,  $E$  is the elastic modulus of the connector's material, Pa,  $S$  is the cross section area of the connector,  $m^2$ ;

IV. Weighting the surface of the RC panels;

V. RC panels freezing to the soil.

It is assumed that the pile cap and field under the GCU are identical to those of compressor stations no. 2 Olekminskaya and no. 6 Skovorodinskaya of the Sila Sibiri main gas pipeline. The foundation consists of a 77.6-ton surface steel pile cap and a field of 44 piles that are 426-mm pipes with 9-mm-thick walls made of the 09G2S steel (the depth of pile penetration is 12 m, the mass of a pile is 1158 kg). The underlying soil is 3 meters of made ground consisting of medium-grained sand. Below the depth of 3 meters lies icy loam in a solidly frozen state. In summer, the top layer of soil thaws to the depth of 2 meters, at the end of winter, the underlying soil, including the top layer of the made ground, is in a solidly frozen state. The temperature of the soil 12 meters below the grading level is  $-1.5^\circ C$ . The distribution of temperatures and elastic moduli of frozen soils through the depth of the underlying soil for the warmest and coldest times of the year is shown in Fig. 3.

### 3. Symmetrical and non-symmetrical attachment of the device

Let us take a look at the simulation results with symmetrical attachment of the device [1] to the foundation in summer and winter. Fig. 4 shows the resulting figures of the foundation's vibration amplitudes caused by one of the components of the total recurrent load  $P_3 \cdot \sin(\omega_3 \cdot t)$ .

Out of the graphs in Fig. 4A and 4B, it can be seen that the symmetrical attachment of 2 RC panels in winter reduces the maximum vibration amplitude  $A_{max}$  by 17.2%, while increasing the number of attached panels from 2 to 4 has practically no effect on the changes of  $A_{max}$ . At the same time, the attachment of 2 and 4 RC panels in summer reduces  $A_{max}$  by 38.5% and 42.4% respectively.

Due to the tight arrangement of the process equipment, a non-symmetrical attachment of the RC panels to the foundation may also be justified, e.g., on one side only (see Fig. 5). In this case, with the same number of attached RC panels,

the simulation shows vibration displacements decrease by 5.8% in winter and by 25.6% in summer.

Simulations shows that increasing the number of non-symmetrically attached RC panels from 2 to 4 does not affect the change of  $A_{max}$  either in summer, or in winter. Thus, a non-symmetrical attachment of more than 2 RC panels is not advisable (see Fig. 5C). The positive effect of non-symmetrical attachment of RC panels is lower by 16.8...32.8% as compared to the symmetrical solution. The advantage of this layout though is its versatility, especially when the process equipment is spaced closely around the GCU foundation.

### 4. Attachment of RC panels at different distances from the central axis of the foundation

Let us consider  $A_{max}$  for four cases of one RC panel attachment at distances of 5.25 m, 11.25 m, 17.25 m and 23.25 m from the central axis of the foundation (see Fig. 6). The attachment of an RC panel at a distance of 5.25 m reduces the  $A_{max}$  by 22.7%, while the attachment of the same panel at distances of 11.25 m, 17.25 m, 23.5 m reduces the vibration amplitude by 3.7%, 2.2% and 1.4% respectively. Thus, if the length of the connector increases 4 times, the effect of reduced vibration amplitude decreases 16 times.

The efficiency of a connector with the rigidity ratio of  $452760 (H \cdot M^2)/M^2$  (made of a 90 x 90 mm square tube with a 7 mm-thick wall), provided that the distances between the panel and the foundation axis are more than 10 m and 20 m, is less than 5% and 2%, respectively. Obviously, in order to increase the effect of RC panel attachment, the connector stiffness should be increased as well.

### 5. Attachment of RC panels through connectors with different stiffness ratios

Based on the comparison of the AFRs of foundations with symmetrically attached RC panels with the connector stiffness ratios ranging from  $175560 \text{ kN/m}^2 \cdot \text{m}^2$  to  $2251200 \text{ kN/m}^2 \cdot \text{m}^2$ , curves were constructed that show the dependence of  $A_{max}$  and  $\lambda_{A_{max}}$  on the stiffness of the connectors in

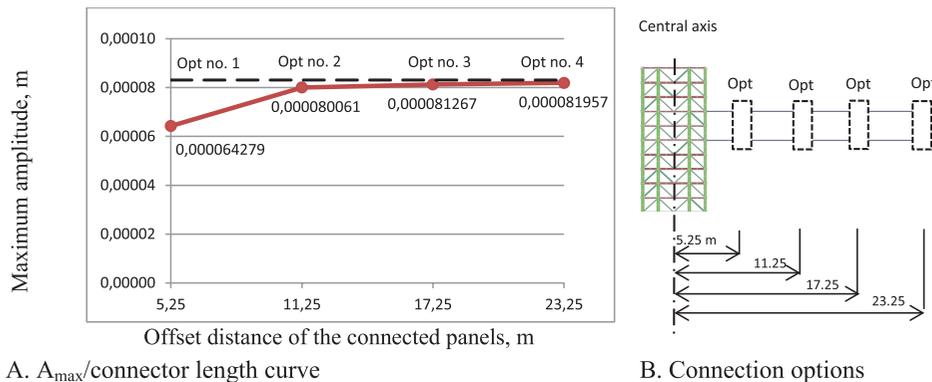


Fig. 6. Comparison of  $A_{max}$  for four cases of attachment of equally spaced RC panels

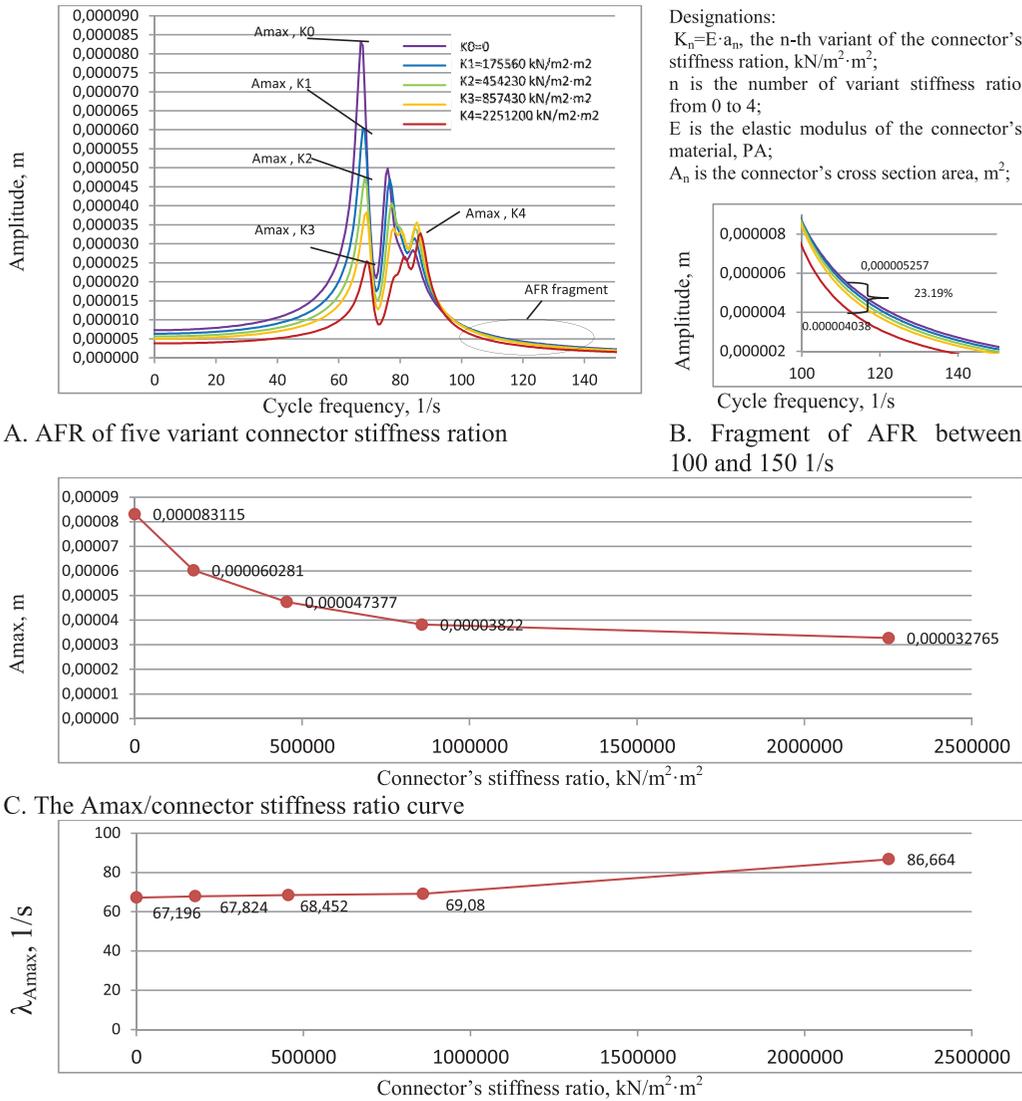


Fig. 7. Correlation between the foundation's AFR and the connectors' stiffness ratio

Fig. 7 C, D, where:  $\lambda_{A_{\max}}$  is the frequency of the foundation's own vibrations corresponding to  $A_{\max}$ . As the stiffness of the connectors grows from zero to 2251200  $\text{kN/m}^2 \cdot \text{m}^2$   $A_{\max}$  decreases 2.53 times, while  $\lambda_{A_{\max}}$  increases by 28.97%. Within the frequency range between 100 and 150 1/s, the vibration amplitude reduction is over 23% (see Fig. 7 B).

Thus, the approach that involves increasing the connectors' stiffness is well applicable to GCUs with a cycle frequency of exposure to dynamic loads of more than 100 1/s, e.g., gas turbine GCUs.

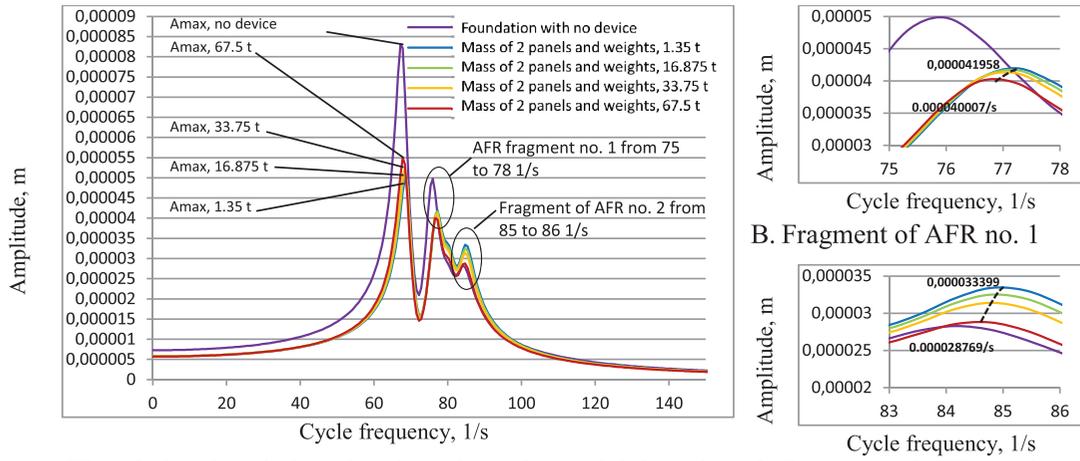
## 6. Weighting the surface of an RC panel

An analysis of the amplitude-frequency response has shown that increasing the total mass of  $M_{wt}$ , i.e., two RC panels with additional weights symmetrically attached to the foundation, does not affect the reduction of  $A_{\max}$ , but, on the contrary, within the frequency range between 67.5 and 68.45 1/s, as  $M_{wt}$  increases from 1.35 t to 67.5 t, the growth

of  $A_{\max}$  is 9.3%, while  $\lambda_{A_{\max}}$  decreases by 0.93%. At the same time, within the frequency range between 76 and 78 1/s, the maximum vibration amplitude and the corresponding frequency decrease by 3.73% and 0.819%, respectively. A similar situation can be observed within the frequency range between 83 and 86 1/s (see Fig. 8 B, C).

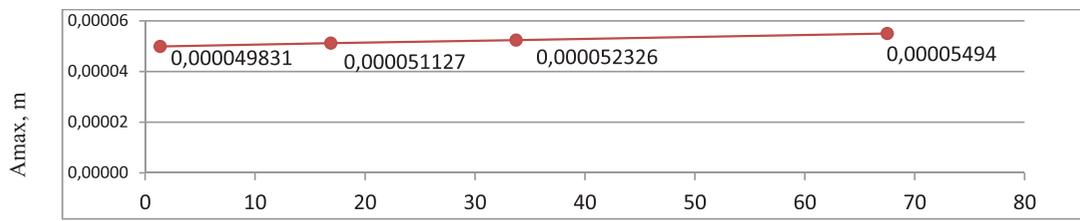
The results of GCU analysis show that increased weight of the attached RC panels within the frequency range up to 70 1/s does not allow reducing  $A_{\max}$ . At the same time, within the frequency range between 76 and 78 1/s, the increase of the mass of the RC panels from 1.35 t to 67.5 t decreases  $A_{\max}$  by 3.7%, while within the frequency range between 83 to 87 1/s,  $A_{\max}$  decreases by 16.1%.

Increasing the mass of the attached RC panels is quite efficient in the case of GCUs with a cycle frequency of rotor rotation of more than 83 1/s, which roughly corresponds to 800 ... 850 revolutions per minute. At the same time, for GCUs with the speed of rotor rotation of less than 800 ... 850 revolutions per minute, the opposite effect is observed that involves increased vibration amplitude.

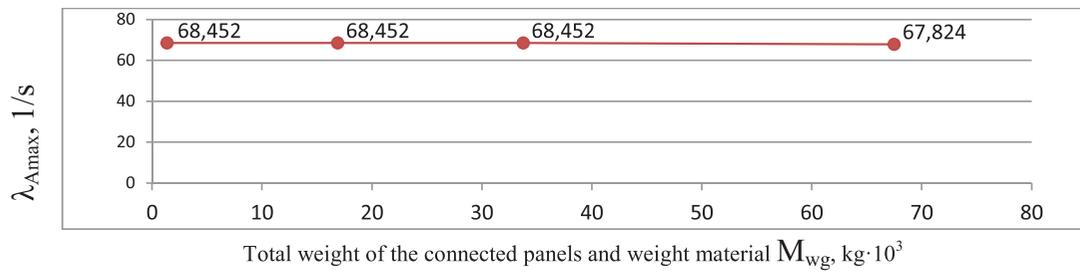


A. AFR of the foundation for 4 options for weighting the connected RC panels

C. Fragment of AFR no. 2



D. Amax/connected RC panel weight curve



E.  $\lambda_{Amax}$ /connected RC panel weight and weight material curve

Fig. 8. Correlation between the foundations' AFR and the mass of the attached RC panels and weight material

### 7. RC panels freezing to the soil

The authors identified the AFR of a foundation with attached RC panels for the cases of underlying soil freezing together with the RC panel to the depths of 0.5 m, 1.0 m, 1.5 m, 2 m, 2.5 m (see Fig. 9). An RC panel's freezing to the underlying soil is ensured by a refrigerant circulating through special cavities within the panel [1]. The freezing can also be done using a system for horizontal thermal stabilization of soil [6].

The comparison of the AFR of a foundation with attached RC panels for five cases of freezing and the case of no freezing shows a decrease of  $\lambda_{Amax}$  by 21.1% and 17.2% in cases of freezing of the RC panel with the underlying soil to the depths of 0.5 m and 2.5 m, respectively (Fig. 10 C).

It must be noted that, on the one hand, the increasing volume of soil freezing with an RC panel adds more mass to the attached frozen soil, thus contributing to the decreasing frequency of the

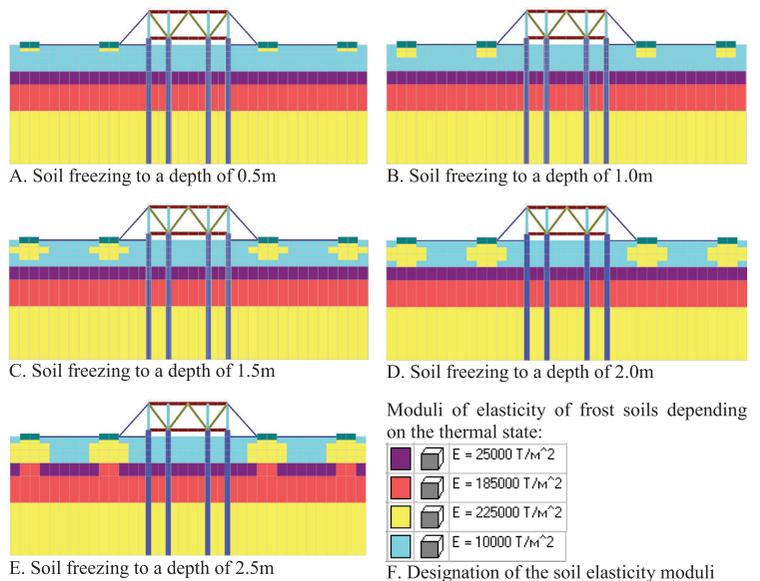


Fig. 9. Possible depths of soil freezing to RC panels

foundation’s own vibration, and, on the other hand, as the size of the frozen soil grows, the stiffness of the foundation – RC panel system and the frequency of own vibrations increases. When the underlying soil freezes to the RC panel to the depths of 0.5 and 2.5 meters,  $A_{max}$  increases by 118.1% and 46%, respectively (see Fig. 10 B).

Using simulation and numerical experiments, the AFR of a foundation was defined for the following cases: symmetrical and non-symmetrical attachment of the device, attachment involving varying numbers of RC panels at different distances with different connector stiffness ratios, as well as with additional weights on the surface of the RC panels and taking into account the depth of RC panel freezing with the underlying soil.

It should be noted that the best possible effect in the form of reduced  $A_{max}$  and  $\lambda_{A_{max}}$  in cases of attached RC panels is achieved when they are attached to the foundation symmetrically (see Fig. 5 B).

The effect can be enhanced by increasing the stiffness of the connectors (Fig. 7 C) or reducing the distance between the attached panel and the foundation, if that is allowed by the environment, in which the process equipment is installed (see Fig. 6 A). In this case, the desired result can also be achieved if the arrangement of the RC panels is non-symmetrical (see Fig. 5 C, D).

Increasing the mass of the attached RC panels by means of additional weights or soil freezing [1] also allows reducing  $A_{max}$  and  $\lambda_{A_{max}}$ , but only within the frequency range above 1000 revolutions per minute. That can be used for gas turbine GCUs with the minimum operating rotor speed of 3000...3500 rpm. At the same time, in the case of units with the rotation speed of 1000 rpm and less the use of this approach requires additional research.

### 8. Conclusion

The Method examined in the paper is characterized by its simplicity and improved dependability, as it allows using concrete blocks, cement mortar, cemented sand, etc. for weighting RC panels.

The study identified that in the case of symmetrical connection of four reinforced concrete panels in summer, the reduction of vibration displacements is 42.4%, while increased stiffness of the connectors, attachment of additional weights and freezing of reinforced concrete panels into the ground will allow reducing the vibration displacements of the foundation up to 2.5 times. Dependability simulation has shown the effectiveness of the method in the cold and warm seasons:

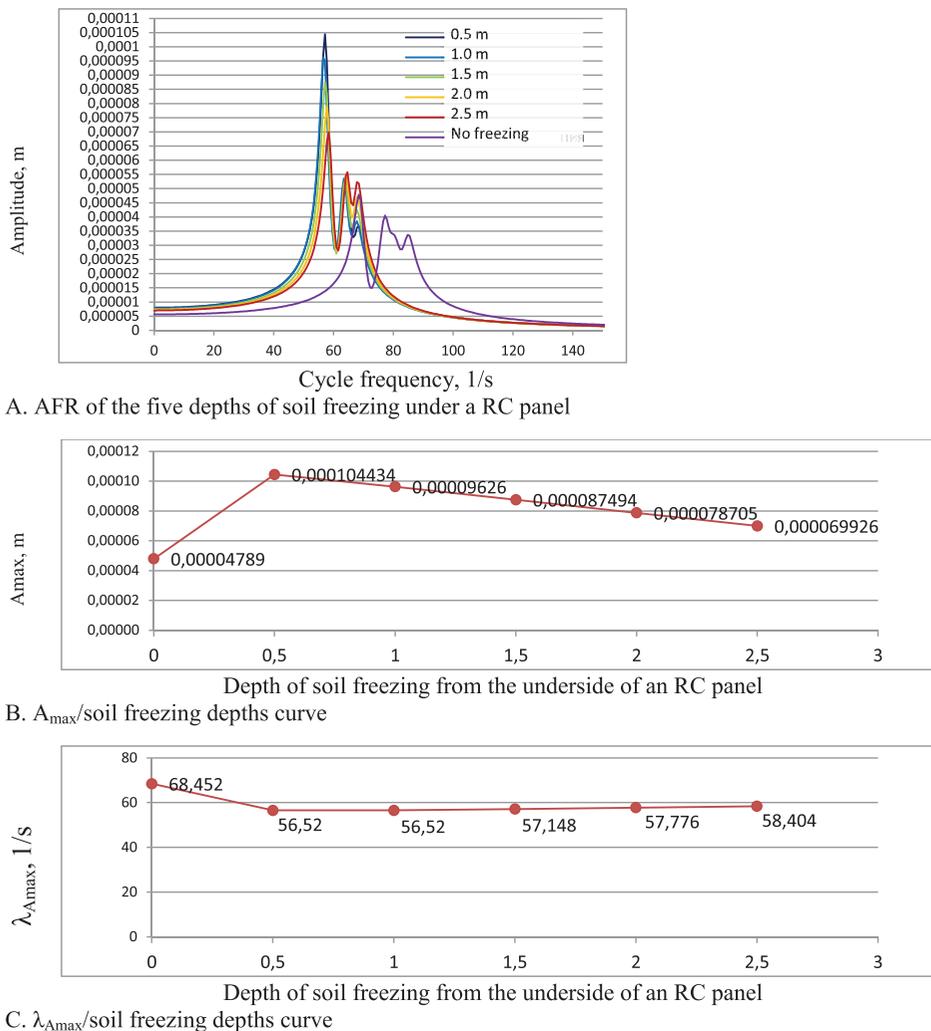


Fig. 10. Correlation between the foundations’ AFR and the depths of soil freezing under an RC panel

- in case of symmetrical and non-symmetrical connection of RC panels;
- with RC panels at different distances from each other and from the foundation;
- with connectors with different stiffness parameters;
- with additional weights;
- when frozen to the ground.

Research dedicated to improving the dependability of foundations exposed to vibration load is underway not only in Russia, but abroad as well [7, 8, 9, 10, 11].

In conclusion, it should be noted that applying the Method requires additional research and development activities, since the above computational experiment results show sufficiently good indicators of reduced vibration displacements of foundations. However, applying the findings in the process of development of project documentation and construction of foundations requires R&D activities involving verification and comparison of the obtained results of numerical simulation with a natural experiment.

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## The authors' contribution

**Tyurin M.A.** formulated the study's key idea, defined the task and developed the approach to its solution.

**Bocharov M.E.** analysed subject-matter literature, drawn up the paper's conclusions.

**Vorontsov M.A.** contributed to the task definition and solution development, discussion of the research methods and findings.

**Melnikova A.V.** contributed to the discussion of the research methods and analysis of the findings.

## Conflict of interests

The authors declare the absence of a conflict of interests.