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Evaluation of Stability of Electric Transmission Concrete Poles Under the Influence of Blast-Induced Ground Vibrations on the Basis of Numerical Modelling

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Abstract. For the moment, a large number of mining enterprises in Russia engaged in the open-pit mining face with the problem of providing the stability of the directly-embedded concrete poles which are a part of the overall transmission power line system. The blasting operations considered to be an efficient way of developing the deposits strongly affect the concrete poles in the immediate vicinity from the quarries. The major part of electric poles near the deposits has critical deflections from the vertical position. The process of evaluating the stability of the poles affected by the blast-induced ground vibrations should inevitably include the process of determining the criterion of the loss of stability that will help to evaluate the level of the ground vibrations safe for the construction. The paper presents the methodical approach of evaluating the stability to be performed with the help of the finite element model and studies of the stability of a construction having various angles of deflection.

1. Introduction

An issue of ensuring the stability for supports of the overhead electricity power lines affected by the blasting operations of the nearby quarries is of critical importance for enterprises not depending on the type of the extracted raw materials. As well, the growth of the supports deflection is a matter of time: blasting operations at the deposits with the low rates of extraction may affect the constructions during a period of time reaching the critical level of deflection in contrast to the situation at quarries or open-cut ore-mines with the large-scale rates of extraction: the critical vibrations of the construction may occur after a single blast.

Rates of extraction at the gold ore fields like the Olympiadinsky mining and processing complex which is considered to be one of the hugest in Russia are very high; to provide the volume of ore extraction of 12.2 mln tons per year an enterprise performs the blasting operations and whereas the electronic systems of initiation are used, the maximal mass of explosive per delay time may reach 1.9 t. The overhead electricity power line with the steel tower supports are affected by the ground vibrations which results in the stability loss.

Another type of supports which are also regarded as sensitive to vibrations by reason of being directly embedded into the ground is a free-standing electric poles. This type is the most widespread – about 60-70 % of all types of supports. Very often the sections of these poles approach to the open-pits up to the critical distances. For instance, the Afanasevskoye deposit of cement raw materials (Moscow region) and Borshevskoye deposit (Kaluga region) faced with the problem of ensuring the stability of



concrete poles; the distance between the front of mining operations and the poles is about 400 m and is going to be reduced. Though the rates of extraction at such enterprises are not so high, maximal mass of explosives per delay time may be equal to 0.6 t as well as the geometrical dimensions of a block are several times less in comparison with ore field deposits, the problem of concrete poles stability loss is also of great importance.

2. Literature review

There is a set of studies devoted to various aspects of electricity power lines supports behavior under various types of loading including the combinations of climatic loads, the rupture of insulators or cables [1, 2], vibrations due to earthquakes, structural behavior of spun-cast poles, steel and polymer with the prestressed reinforcement [3], dynamic performance of the supports [18-20].

Urgessa et al. (2016) studied the influence of geometric characteristics, fiber orientation of the fiber-reinforced polymer composite poles on the basis of the finite element analysis. A range of studies (Kaminski, 2014), (Alminhana, 2015) are devoted to the investigation of supports behavior after a rupture of cables or insulators. After the series of calculations regarding the combination of wind loading and the conductor failure, the authors concluded that the latter considerably amplifies the response of a system making the whole system unsafe. Rao (2004) investigated the deflections of tower lines and the fundamental frequencies and derived the equations which may be used for prediction of the deflections and the frequencies. Bo-Chen et al. (2014) studied the dynamic responses of the tower-line system: the wind responses including strong winds like tornado, downburst, etc.; seismic responses; ice-induced responses. The studies of the structural behavior of the pole structures subjected to blast-induced ground vibrations are limited: Chen (2010), Dai (2009) investigated the dynamic performance of poles structures (coupled systems).

Free-standing directly-embedded concrete poles of all types are kept in the designed vertical position by the soil reaction along the lateral surface of the pole. Soil strength and deformation characteristics play a key role in ensuring the stability [4]. For the reason of long mileage of the electricity lines the soil properties usually alter a lot from one support to another and sometimes if the strength characteristics of a soil (friction angle and cohesion) may provide the strength of the soil foundation, i.e. the bearing capacity of a soil, the deformation characteristics (deformation modulus), at the same time, may not have the minimal required value to provide the stability. In this case the study of the influence of the deformation modulus on the pole stability is important as well as the effect of the initial angle of deflection on the value of the resultant deflection and stress-strain state of the soil.

3. Methodological basis

3.1. Methodological basis for vibration registration

The monitoring of blast-induced ground vibrations was performed on the basis of Afanasevskoye deposit of cement raw materials (Moscow region). The registration of the seismic signals of 4 blasts was realized with the help of register modules which were placed both on the ground and fixed at the concrete pole [5,17]. The vibration of the ground (the velocity of vibrations) was registered by MinimatePro4 seismic recording system – a four-channel meter model (four record channels for one three-axis geophone (ISEE or DIN) and linear ISEE microphone).

3.2. Condition for service limit state design

An anchorage design of free-standing concrete poles consists in considering the overturning horizontal forces and moments in the vertical plane.

To ensure the stability of a concrete free-standing pole the following condition should be satisfied:

$$\beta \leq \beta_u \quad (1)$$

where β - a deflection angle of concrete pole under the influence of horizontal loads; β_u - a maximum allowable value of a deflection angle.

According to the requirements of Russian Design Code [4,6] for directly-embedded concrete poles, the ultimate deflection angle should not exceed 0.01 radian.

The equation for a deflection angle includes deformational characteristics of subsoil:

$$\beta = \frac{3Q}{4Eh^2}(6\alpha + 3) \cdot \nu \quad (2)$$

where Q - a designed horizontal force influencing on the pole; E - soil modulus of deformation; ν - dimensionless factor, depending on the geometry characteristics of the pole subsoil part.

3.3. Time-history analysis (ABAQUS)

The numerical model was created according to real geometrical characteristics of an electric pole; the physical and mechanical characteristics of the soil correspond to those which were obtained after laboratory studies.

A dynamic time-history analysis [7,8,9] was performed on the basis of implicit integration scheme.

4. Results and discussion

4.1. Vibration registration results

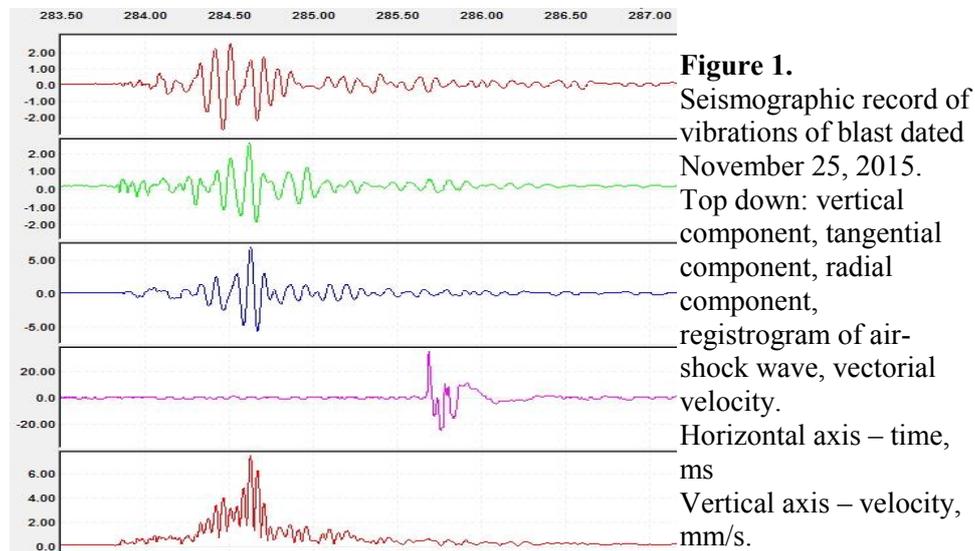
The results of monitoring to be performed at the quarry are represented in the table 1. The registration of each blast was performed simultaneously at three registration points. The maximal peak particle velocity equal to 23.94 mm/s was registered on the ground at the distance of 170 m from the block and refers to the explosives mass of 492 kg for a time delay. The velocity of vibrations of a pole increases in proportion to the reduction of a distance between the blast and the pole [10-12].

Table 1. Results of blast monitoring (Afanasevskoye deposit).

No	Rock type	Drillability grade	Max. amount of explosives per delay time, kg	Max. velocity of pole vibration, mm/s	Max. velocity of ground vibration (vectorial), mm/s	Epicentral distance, m
1	Marlstone	IV-VI	492	-	23.94	to block 170
			492	-	7.5	to block 350
			492	0.95	-	to pole 800
2	Limestone	IV-VI	300	-	10.0	to block 150
			300	-	6.06	to block 300
			300	1.14	-	to pole 700
3	Marlstone	IV-VI	376	-	8.36	to block 210
			376	-	7.51	to block 225
			376	4	-	to pole 450
4	Marlstone	IV-VI	482.6	-	19.09	to block 210
			482.6	-	14.24	to block 290
			482.6	4.4	-	to pole 400

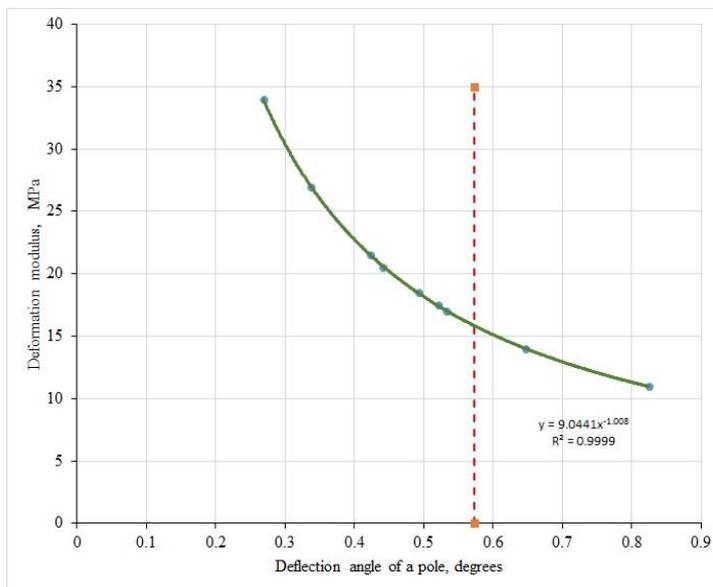
The seismic signal registered on the ground at the distance of 350 m from the block is shown at fig. 1. Maximal vectorial velocity which was registered is equal to 7.5 mm/s which refers to the blast

N 1. Analyzing the seismogram we may divide the initiation of the first and the second group of boreholes – it may be clearly seen at the vertical component and the vectorial velocity. The presented seismogram will be further used to perform the time-history analysis on the basis of Abaqus [15].



4.2. Deformation modulus and deflection angle pattern

The clayish soils are classified by the consistency index [13,14]. The clays, sandy clays of hard and medium-hard consistency are considered to be a good natural soil foundation.



The studies of the soil foundation at the Afanasevskoye deposit showed that the soil belongs to medium-hard group by the consistency index.

The deflection angle of a pole and deformation modulus pattern was studied (fig.2). The general trend shows that the stability of a pole may be provided with the deformation modulus exceeding the value of 15 MPa. Further decrease of this characteristic leads to the critical angle growth. The stability of the poles in such soils may be ensured only with the help of special measures (for example, placing horizontal beams near the foundation [16]).

4.3. Cyclic loading study results

In order to study the cyclic loading of a pole a seismogram with the ground vibrations registered at the distance of 450 m to a pole (fig.1) was chosen as a dynamic load. A sequential loading of a pole by a cycle of dynamic loads registered from the same blast was performed in order to evaluate the pole accumulated deflection.

Figure 4 demonstrates the displacement of the top of a pole under the cyclic loading. Generally, the movements of a top repeats the movements of a ground (the outlines of a registered signal).

Analyzing the graph of cyclic loading of a pole we may see that a pole deflection amplitude and amplitude of a dynamic load pattern has a linear character (the larger the amplitude of a dynamic load the larger the deflection of a pole). For the reason that the seismic vibrations to be registered at the quarry do not cause the plastic deformations in the subsoil in the far zone of a blast the stated above pattern has a linear character.

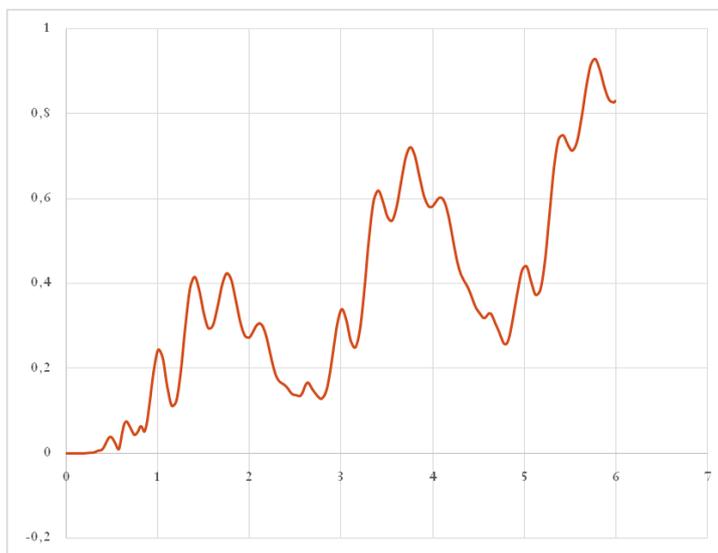


Figure 3. A diagram of cyclic displacement of a pole top affected by cyclic load from a seismic wave. Residual strain growth as a linear function. Horizontal axis – time, s. Vertical axis – displacement, mm.

After a wave propagates in the pole and the vibrations of a pole attenuate, there is still a certain value of a residual deflection which is accumulated; the value of a residual deflection grows from one blast to another (fig.3). Using this pattern we may estimate the approximate number of blasts at the quarry which will lead a pole to a critical deflection.

Table 2. The influence of the initial deflection angle of a pole.

Initial angle of deflection, degrees	Initial value of deflection, m	Resultant values of deflection due to external forces (vertical load), m	Value of stresses in the soil, MPa
0.25	0.113	0.456	0.024
0.5	0.226	1.158	0.975
0.75	0.340	1.723	1.927
1.0	0.453	2.508	2.345

The influence of the initial value of a pole deflection on the value of stresses in the subsoil is represented in Table 2. The value of deflection equal to 1 degree is considered to be critical as further growth of deflection angle leads to the occurrence of plastic deformations in the soil exceeding the bearing capacity of a soil and leading to the stability loss.

5. Conclusions

The following conclusions can be made as the result of the performed studies:

- The analysis of the influence of the initial angle of deflection on the stress-strain state of subsoil was studied. The critical value of the initial angle was obtained.
- The investigation of the cyclic loading of a pole structure loaded by series of blasting vibrations was made; the linear pattern of a residual value of a deflection angle under the sequential loading was derived.
- The critical value of the elasticity modulus for clayish soils below which the stability of a pole may be ensured only with special measures was determined.

The represented results are a part of the study of dynamic analysis of the transmission pole structures under blast-induced ground vibrations. Future studies will include the modal analysis of the pole, the dynamic analysis of the load under various types of blasting vibrations.

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