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ASPECTS REGARDING STATIC STABILITY AND DYNAMIC STABILITY OF THE TOWER CRANES

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Abstract: Tower cranes are widely used in construction works, because they are used to mechanize the works. Specialized for tall constructions, tower cranes have proven to be the most economical type of cranes. They are used for loading-unloading, transport and assembly operations on civil and industrial construction sites and their characteristics vary within very wide limits. Stability is an important indicator when sizing cranes. The stability condition requires that the resultant of the vertical forces be inside the support polygon, or, in other words, the load on all the bases should acquire positive values. The present paper presents some aspects related to static stability and then a study on the dynamic stability of tower cranes. The case of dynamic stability in transient regimes will be analyzed on a concrete case of a tower crane, followed by an analysis of the stability to wind and earthquake for these types of lifting machines.

Key words: tower cranes, tall constructions, static stability, dynamic stability, transient regimes, stability to wind and earthquake.

1. INTRODUCTION

Tower cranes are widely used in construction works because they help to mechanize the works. Due to the definite advantages that tower cranes present, construction companies currently offer a wide range of types and dimensions to the beneficiaries [1].
These families of cranes are initially designed with a limited number of models. Later, depending on the needs, their number increases by inserting an intermediate model, following its testing, between two neighboring models. By perfecting the model, the aim is to improve the technical-economic indices of the tower crane.
A type of crane with a wide spread on construction sites today is the tower crane with a horizontal arm. This type of crane serves a large domain of work, due to the large length of the arm and due to the fact that it has a high lifting height [1, 2].

2. MATERIALS AND METHODS

In the following, some aspects will be presented regarding a type of tower crane frequently used on our construction sites, the MT 30 tower crane. MT 30 cranes are used on construction sites for loading-unloading and assembly operations for buildings with up to 10 floors. The cranes mounted without the upper sections of the tower are used in warehouses, for loading-unloading works, [3].
The crane is equipped with pliers for fixing the portal to the rails and with a height limiter. The maximum load is 3 tf (30 kN), the maximum lifting height is 38 m, and the maximum range is 20 m (figure 1, [4]).
Stability is an important indicator when sizing cranes. The stability condition requires that the resultant of the vertical forces be inside the support polygon.
According to the way forces are considered, there is static stability and dynamic stability. Ensuring stability is done by determining the stability coefficient, which is done in two extreme situations of possible out of stability, respectively under load and in the void [5, 6].
Static stability is a necessary condition for the stability of the crane, but not sufficient. Due to the dynamic demands, the dynamic stability must also be taken into account. Because dynamic demands are much more difficult to evaluate, before making an analysis of dynamic stability, it must be tested if the problem of this type of stability is a real problem or, being a minor problem, it can be included in the conditions that ensure the static stability, [7].


Fig. 1. MT 30 crane, [4]

3. RESULTS AND DISCUSSION

Within this chapter, aspects regarding dynamic stability in transient regimes, stability to wind and earthquake stability will be presented.
In order to determine the dynamic stability in transient regimes, an analysis will be made on a concrete example. A tower crane, represented in figure 2, is considered for the study.

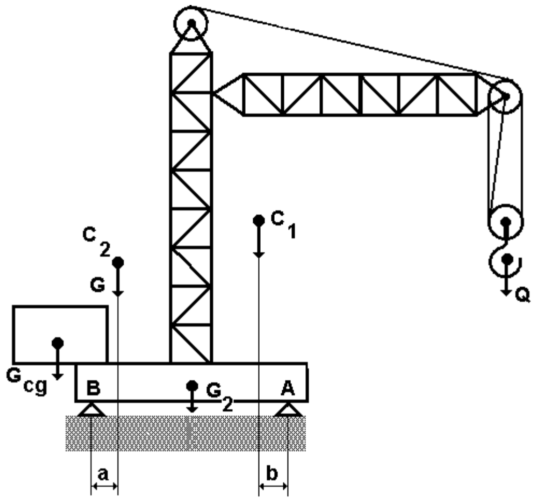

Fig. 2. Tower crane model for the study of dynamic stability in transient regimes, [1]

In figure 2, the notations are:
Q = load from the crane hook, [N];
G = the crane weight, [N];
G_{cg} = the counterweight weight, [N];
G_2 = chassis weight, [N];
C_1 = center of gravity of the crane, with the load on the hook;
C_2 = center of gravity of the crane, without load;
A = the previous bearing point against which the stability under load is evaluated;
B = the posterior bearing point against which the stability in the void is evaluated.
Under the effect of the load from the hook, the elastic metallic structure of the crane deforms and stores potential deformation energy, W_p. At the sudden loss of the load from the hook, this energy is released and, being able to perform mechanical work, it can produce the displacement of the crane or some parts of its structure [1].
In an extreme case, the crane can overturn around point B. Around this point (point B), the center of gravity C_2 describes an arc of a circle with radius $R=BC_2$ and, for complete overturning, an overturning mechanical work is required, given by the formula (1):

$$L_{mec\,rast} = G \cdot \delta = G \cdot R(1 - \cos\alpha) \quad (1)$$

where: δ = the upward displacement of point C_2 on the circular arc with the center in B;

α = the angle between the vertical direction through B and the direction BC_2.
Analyzing the formula (1), two situations can appear:
a)if the potential energy accumulated through the elastic deformation of the structure is greater than the mechanical work, i.e. if is satisfied the inequality:

$$W_p > L_{mec\,rast} \tag{2}$$

then the crane can overturn.
Overturning depends on a multitude of factors, the most important of which are:
❖the release speed of the potential energy, compared to the overturning speed, taking into account the inertias which controls this movement;
❖the amplitude of the elastic deformation in the opposite direction of the structure, which can take over a large part of the stored potential energy, remaining a fraction that may or may not overturn the crane.
These situations can only be detected through a complete and complex dynamic study of the entire structure, possible to do with a software based on finite element analysis [8].
b)if the potential energy accumulated through the elastic deformation of the structure is lower, at most equal with mechanical work, i.e. if is satisfied the inequality:

$$W_p \leq L_{mec\,rast} \tag{3}$$

then the crane will surely not tip over.
This condition, if it is possible to ensure to the cranes, eliminates from the start the need to approach the studies using the finite element analysis specified above.
To exemplify this possible state, a concrete case was chosen, presented in figure 3.

G_1 = tower weight, [N];
G_2 = chassis weight, [N];
G_3 = arm weight, [N];
The tower and the arm are in lattice beam type construction and their deformations were calculated with a specialized software for finite element analysis of spatial structures.
G_{cg}= counterweight weight, [N];
h = tower height, [m];
l = arm length, [m];
x_1 = coordinate of weight forces G_1 and G_2 on the abscissa axis in a conveniently chosen xBy coordinate system;
x_2 = the position of the previous bearing point A compared to the support of the weight forces G_1 and G_2 in the same coordinate system;
x_{cg}= coordinate on the abscissa axis of the force G_{cg}.
The numerical values are:
$h = 20\ m$; $l = 10\ m$; $x_1 = x_2 = 3\ m$; $Q = 20000\ N$; $G_1 + G_3 = 16398\ N$;
where:
$G_1 + G_3$ = the weight of the tower and arm structure obtained from the specialized software for the analysis of spatial structures;
$G_1 = 13378\ N$; $G_3 = 3020\ N$.

$$G_0 = G_1 + G_2 + G_3 \tag{4}$$

The specialized calculation software offers the following results:
$x_{G_1} = 3\ m$; $x_{G_2} = 3\ m$; $x_{G_3} = 8\ m$; $y_{G_1} = 10.5\ m$; $y_{G_2} = 0.25\ m$; $y_{G_3} = 20.5\ m$; $x_{G_0} = 3.67\ m$; $y_{G_0} = 9.10\ m$.
Static stability is determined under load or in void.
The stability coefficient under load is defined as the ratio between the sum of the moments relative to the overturning axis of the crane of all forces acting on the crane (with the exception of the load moment) and the load moment. This coefficient indicates the overload limit of the crane at which it is still stable. In order to exaggerate in the sense of ensuring stability, it is chosen a higher value of the coefficient, namely 1.2 instead of 1.15, as proposed by the specialized literature, [1].

$$\frac{G_{cg} \cdot (x_{cg} + x_1 + x_2) + G_0 \cdot (x_1 + x_2 - x_{G_0})}{Q \cdot (l - x_2)} \geq 1.2$$

The stability in void coefficient is defined as the ratio between the sum of the moments relative to the overturning axis of the crane of the forces given by the weights of the elements that tend to maintain the crane in a state of equilibrium and the sum of the moments (relative to the same axis) of the forces given by the weights tending to overturn the crane, [9].

$$\frac{G_0 \cdot x_{G_0}}{G_{cg} \cdot x_{cg}} \geq 1.2$$

Substituting the concrete numerical values in the relations above, it is obtained:

$$\begin{cases} G_{cg} \cdot x_{cg} + 6 \cdot G_{cg} \geq 115812.66 \\ G_{cg} \cdot x_{cg} \leq 68500.55 \end{cases}$$

Three groups of values for x_{cg} and G_{cg} will be considered:

$$\begin{array}{lllll} x_{cg} = 1 \Rightarrow & 16545 & \leq & G_{cg} & \leq & 68501 \\ x_{cg} = 2 \Rightarrow & 14477 & \leq & G_{cg} & \leq & 34251 \\ x_{cg} = 3 \Rightarrow & 12868 & \leq & G_{cg} & \leq & 22834 \end{array}$$

From the values above the following set was chosen:

$$\begin{cases} x_{cg} = 2 \ m \\ G_{cg} = 30000 \ N \end{cases}$$

from which it follows:

$$G = G_0 + G_{cg} = 52398 \ N$$
$$x_G = 0.42 \ m; y_G = 5.03 \ m$$
$$\alpha = arctg \frac{x_G}{y_G} = arctg \frac{0.42}{5.03} = 4.77°$$
$$\overline{BC_2} = \sqrt{0.42^2 + 5.03^2} = 5.05 \ m$$
$$L_{mec\,rast} = 916.468 \ J$$

Next, aspects related to stability to wind are detailed in the paper.
The forces determined by the wind pressure act on the cranes installed in the open air. The calculation method of these forces is standardized. The force resulting from the action of the wind on an element of the crane construction is determined for the first face of the element exposed to the action of the wind with the mathematical expression:

$$F_v = K \cdot g_v \cdot A \cdot \phi \cdot \beta \tag{5}$$

and for the following faces with the mathematical expression:

$$F_v = K \cdot g_v \cdot A \cdot \phi \cdot \beta \cdot \eta \tag{6}$$

Under these conditions, for the entire element, the total force will be:

$$\sum F_v = K \cdot g_v \cdot A \cdot \phi (1 + \eta) \cdot \beta \tag{7}$$

where:
K = coefficient of the resultant of pressures;
g_v = basic dynamic pressure, [N/m^2];

A = area of the contour of the surface exposed to the action of the wind, projected on its normal direction, [m^2];
ϕ = coefficient of fillings;
η = the reduction coefficient of the resultant of pressures;
β = dynamic coefficient.
The force of the wind acts in the horizontal direction and is applied in the center of pressure of the considered surface. The force which cames from the action of the wind on the load is transmitted to the structure at the bearing point of the lifting cable on the structure, [10].
The basic dynamic pressure results from the application of Bernoulli's law of the air flow:

$$g_v = \frac{\rho \cdot v^2}{2} = \frac{v^2}{1.63} \quad (8)$$

where:
ρ = air density at normal atmospheric pressure $\left(\rho = 1.225 \ \frac{\text{kg}}{m^3}\right)$;
v = speed of the air current.
The regulations in force allow the operation of cranes up to a basic dynamic pressure $g_v = 250 \ \frac{N}{m^2}$, corresponding to a wind speed $v = 20 \ \frac{m}{s} = 72 \ \frac{km}{h}$. For tower cranes, operation is limited to the basic dynamic pressure $g_v = 150 \ \frac{N}{m^2} \left(v = 15.6 \ \frac{m}{s} = 56 \ \frac{km}{h}\right)$. These values are used for the calculation of the mechanisms, for the static calculation of the metal construction and for checking the stability of the cranes under load. For fatigue calculations, 60% of the basic dynamic pressure value is considered, [3].
Meteorological records made over a long period attest to the fact that the maximum wind speed and therefore the basic dynamic pressure depend on the geographical area, and within it, the mentioned parameters are lower inside cities than in open territory.
Also, experimental research has established that wind speed and basic dynamic pressure increase parabolically with height. As a result, STAS 10101/20-78 divides the territory of the country into five zones, and within them it indicates basic dynamic pressures, in steps of height, both within the city (in an urban environment) and outside the city (in an open place). These values are taken into account in the calculation of the metal structure, in the calculation of the safety devices against the displacement of the crane (clamps for fixing the crane at the rails), as well as in the calculation of the crane's own stability. If the location of the crane is not known, the data from the extravillain column of zone E (table 1) will be used, in which the basic dynamic pressure is considered constant on height steps of 10 m, [2, 5].
For the calculation, the height of the crane is divided into segments of 10 m each and for each segment the pressure will be considered equal to that corresponding to the maximum height of the segment.
For the automatic calculation, the pressure g_v^H at the height H can be established with the formula:

$$g_v^H = g_v^{10} \left(\frac{H}{10}\right)^{\alpha} \quad (9)$$

where:
g_v^{10} = dynamic pressure at a height of 10 m;
α = coefficient depending on the geographical area (for E area = extravillan, α=0.1).

Table 1. The variation on height of the dynamic wind pressure [1]

Height H (m)	10	20	30	40	50	60	70	80	90	120	150
Pressure $g_v \left(\frac{N}{m^2}\right)$	1100	1170	1220	1260	1300	1320	1340	1350	1380	1410	1440

The graph in figure 4 is made based on the dynamic pressure values presented in table 1 and shows the variation on height of the dynamic wind pressure. The graph shows an obvious increase in the dynamic pressure of the wind with the increase in height.

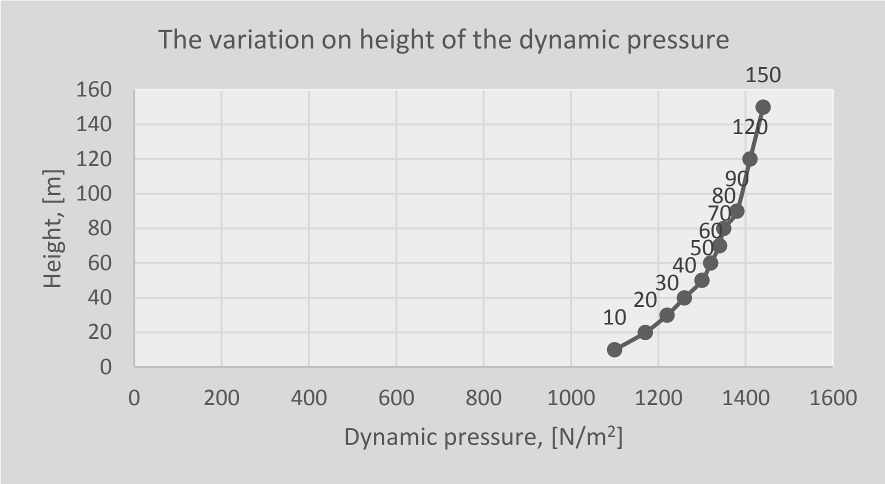

Fig. 4 The variation on height of the dynamic wind pressure

The phenomenon of the air current flowing around an obstacle is particularly complex. The geometry of the air current flowing around and through the latticed metal structure of a tower section, inserted in an aerodynamic tunnel, has a certain schematization that was made based on the photography of the air current in which smoke-producing substances were introduced. The appearance of vortices behind the surfaces exposed to the air current is noted. These vortices create depressions in the respective areas, so that the resultant of pressures is, in general, higher than the basic dynamic pressure and depends on the construction mode of the structure exposed to the action of the wind [7].
The regulations in force (STAS 2843-83) indicate the multiplication of the basic dynamic pressure with the coefficient of the resultant of pressures K, indicated in table 2, where A_i represents the areas of the bars having the same coefficient K_i of the resultant of pressures.
For beams with lattices made of bars with different aerodynamic profile, the coefficient of the resultant of pressures is determined with the formula:

$$K = \frac{\sum K_i \cdot A_i}{\sum A_i} \tag{10}$$

where A_i has the same meaning as above.

Table 2. Coefficient of the resultant of pressures [1]

The elements of the installation to be lifted			Coefficient *K*
Lattice beams with:	bars from laminated profiles		1.6
	bars with square section		1.4
	bars with round section		1.2
Beams with solid heart and caisson beams having the ratio between length l and width h:	$\frac{l}{h}$	20	1.6
		10	1.4
		5	1.3
		2	1.2
Tubular elements where the diameter d is given in [m] and the dynamic pressure g_v in $[\frac{kN}{m^2}]$	$d\sqrt{g_v} \geq 0.1$		0.7
	$d\sqrt{g_v} < 0.1$		1.2
Cabins, covered surfaces, counterweights, cables			1.2
Load			1

The fillings coefficient ϕ represents the ratio between the net area of the surface exposed to the action of the wind and the area of its outline.
For the lattice beams of the lifting machines, the coefficient of fillings usually has values between 0.2 and 0.6. For solid surfaces (without holes) ϕ=1.
For towers with a square section, if the wind acts on the direction of the section diagonal, it is considered that the contour area is the area of one face, but for the coefficient of the resultant of pressures the value:

$$K' = 1.1 \cdot K$$

is adopted.
For lattices structures with a triangular section, the contour area is considered to be the area of one face, and the value:

$$K' = 0.9 \cdot K$$

is adopted for the coefficient of the resultant of pressures.
For loads, their real area is considered. If it is not known, the next value can be adopted:

$$A = A_{sp} \cdot Q \qquad (11)$$

where:
•for loads $Q \leq 5$ t, A_{sp} has the value 1 $\frac{m^2}{t}$;
•for loads greater than 5t, A_{sp} is considered 1 $\frac{m^2}{t}$ for the first 5 t and 0.5 $\frac{m^2}{t}$ for the following ones.
The experimental determination of the dynamic pressure on the faces of a spatial structure, successively exposed to the action of the wind, highlights the fact that on the back faces the pressure is lower than on the first face, as a result of the shielding by the first face of the back faces. The degree of shielding depends on the distance between the faces, their height and the filling coefficient of the shielding face, [9]. As a result, for the calculation of the wind action on the faces following the first face, the prescriptions introduce the reduction coefficient of the resultant of pressures (shielding coefficient) η, whose values are presented in table 3.

Table 3. The reduction coefficient of the resultant of pressures, η [1]

ϕ , $\frac{B}{h}$	0.1	0.2	0.3	0.4	0.5	0.6
	η					
0.5	0.93	0.75	0.56	0.38	0.19	0
1	0.99	0.81	0.65	0.48	0.32	0.15
2	1	0.87	0.75	0.59	0.44	0.3
4	1	0.9	0.78	0.65	0.52	0.4
6	1	0.93	0.83	0.72	0.61	0.5

For B>6h values, η=1 is considered

The evaluation of the distances B and h of the table 3 is done in accordance with figure 5, which represents a scheme for establishing the B/h ratio.

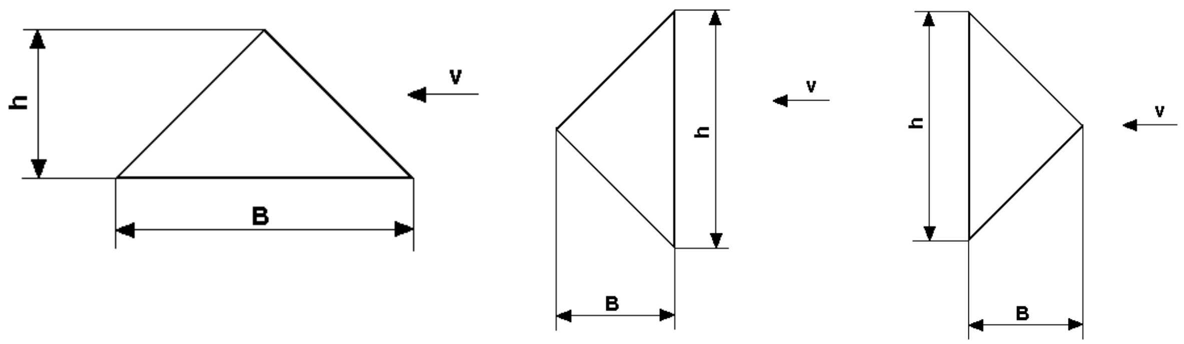

Fig. 5 The scheme for establishing the B/h ratio [1]

The wind speed and therefore the basic dynamic pressure are random characteristics, in permanent variation. As a result, the metal structure of a lifting machine is dynamically loaded, oscillating continuously under the action of the wind. The basic dynamic pressures values indicated in the calculation prescriptions represent average values, obtained by averaging the speed over a certain time interval. In order to take into account in the calculation the dynamic effect of the wind action, the prescriptions introduce a dynamic coefficient β, which multiplies the static action of the wind force and which represents the fluctuations of the dynamic pressure around the average value, corresponding to wind gusts [6].
In accordance with the provisions of STAS 2843-83 and STAS 10101/20-78, the dynamic coefficient has the value β=1 for calculations related to the operating state. For calculations related to the state of rest, the dynamic coefficient is given by the mathematical expression:

$$\beta = 1 + \xi \cdot r \qquad (12)$$

where:
ξ = the amplification coefficient;
r = the gust coefficient, depending on the height of the considered point.
This coefficient is indicated in table 4.

Table 4. The gust coefficient [2]

Height of the considered point, [m]	10	20	30	40	50	60	70	80	90	100	160	200
The gust coefficient, r	0.36	0.34	0.33	0.32	0.30	0.29	0.27	0.26	0.25	0.24	0.20	0.18

The graph in figure 6 is made based on the values for the gust coefficient presented in table 4 and shows the variation of this coefficient depending on the height of the considered point. The graph shows a decrease in the values for the gust coefficient as the height of the considered point increases.

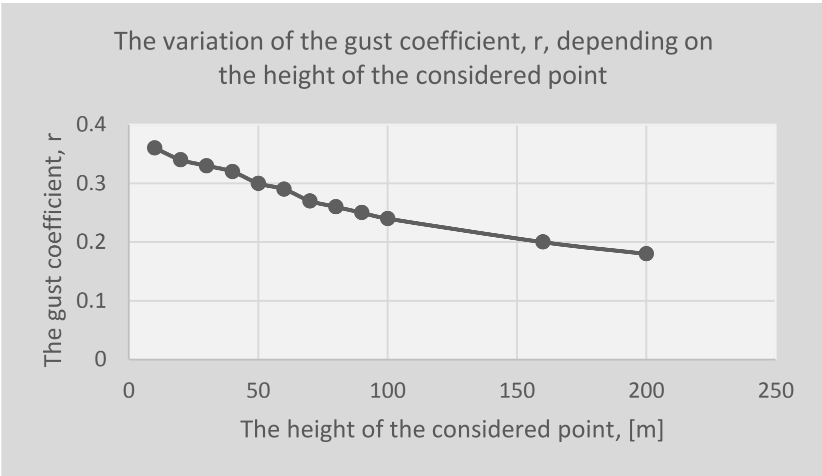

Fig. 6 The variation of the gust coefficient, r

The amplification coefficient ξ is calculated with the mathematical expression:

$$\xi = \xi_1 \cdot \xi_2 \qquad (13)$$

where:
ξ_1 = coefficient that depends on the period of the crane's eigen oscillations;
ξ_2 = coefficient depending on the nature of the construction.
For metal constructions it has the value ξ_2=3.3.
Figure 7 shows the variation graph of the coefficient ξ_1 depending on the period of the cranes' eigen oscillations. It is observed that the values of the amplification coefficient ξ_1 increase with the increase in the period of the cranes' eigen oscillations, the dependence curve being the one represented on the graph. The method of determining the period of eigen oscillations depends on the adopted dynamic model, corresponding to the construction of the crane.
For tower cranes, with the load in the hook, the period of eigen oscillations T, in s, is indicated in table 5 (according to GOST 12994-75). In accordance with the same rules, the period of eigen oscillations for tower cranes without the load in the hook is equal to 2/3 of that indicated in table 5.
Theoretical calculations and experimental determinations carried out for some types of tower cranes (MT 40, MT 50, MTA 125, MTO-180, MTO-450) led to values of the period of eigen oscillations higher by 33...120% compared to the corresponding values in table 5 presented below.

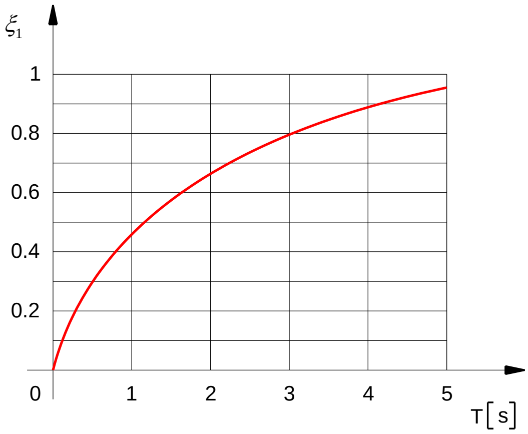

Fig. 7 The variation graph of the coefficient ξ_1 depending on the period T of the cranes' eigen oscillations [1]

Table 5. The period of eigen oscillations to tower cranes [3]

Maximum radius of action, [m]	The height of the arm joint above the ground, [m]									
	< 20		20…40		40…60				60…80	
	The lifting capacity at the maximum radius of action, [t]									
	<5	5-10	10-20	20-30	<5	5-10	10-20	20-30	<10	<10
	The period of eigen oscillations T, [s]									
10	1.5	1.6	1.7	1.9	1.7	1.9	2.2	2.5	2.7	2.9
20	1.6	1.7	1.9	2.2	1.9	2.2	2.5	2.7	2.9	3.1
30	1.7	1.9	2.2	2.5	2.2	2.5	2.7	2.9	3.1	3.4
40	1.9	2.2	2.5	2.7	2.5	2.7	2.9	3.1	3.4	3.7
50	2.2	2.5	2.7	2.9	2.7	2.9	3.1	3.4	3.7	4.0
60	2.5	2.7	2.9	3.1	2.9	3.1	3.4	3.7	4.0	4.5

Next, in this work, some aspects related to earthquake stability will be presented.
Seismic action is an exceptional action that negatively influences the operation of equipments in general and cranes in particular. Exceptional actions are defined as loads that, theoretically, should not appear in the operation of the equipments, but, due to specific or special operating conditions, appear in practice with a very low frequency [3, 6].
Seismic loads influence the behavior of tall cranes, installed in areas with a high degree of seismicity. The seismic action can be assimilated with a horizontal force of variable intensity, applied to the metal structure. Oscillations of the structure introduce additional stresses in its elements.
The dynamic response of the structure depends on its elastic characteristics, and the calculated values depend on the adopted dynamic model. In a first approximation, the action of a horizontal force, applied statically and equal to 2...10% of the crane's weight, can be considered [2].
The verification by calculation of the behavior of the MTA-125 tower crane during an earthquake of the intensity of the one in March 1977 indicated that, at the level of the arm joint, a horizontal force of approximately 4% of the crane's weight develops.

4. CONCLUSIONS

Dynamic requests are, unlike static ones, much more difficult to evaluate. In general, the problems raised by dynamic stability are difficult problems, and their treatment is often done under simplifying and covering assumptions. Using modern means of calculation and algorithms developed especially for laborious calculations and in large numbers, the problem of dynamic stability can be approached from positions very close to reality.
During the study of dynamic stability in transient regimes, for the concrete case considered, a limit value of the mechanical work was obtained, above which, if the potential energy accumulated through the elastic deformation of the structure increases, then the crane can overturn. Below this limit value there is no risk of the crane tipping over.
Research into the dynamic stability of cranes shows that there are possible cases in which the crane overturns due to the too sudden release of the potential energy stored in its structure. This was clearly shown in the work, on a concrete example.
In the case of the study regarding the stability to the wind, both the experimental research and the present paper

showed that the wind speed and the basic dynamic pressure increase parabolically with height.
Ensuring dynamic stability can be done directly, researching cases of dynamic requests and their effect on stability. The energy methods are the most appropriate, indicating almost directly the danger situations and for their application a specialized program product is required, based on finite element analysis.
If it is desired that static stability also ensures dynamic stability, dynamic stability research can be carried out using the methods shown, in parallel with static stability research, and those values of the static stability coefficients can be found that cover dynamic stability as well.

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