Research of the location of fixing blocks in the design of engineering structures

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Abstract. A static model of loads in the mast, cables and blocks fixing its position is investigated. In contrast to the existing installation methods, in which instead of blocks, piles are used, located on the shore and uniquely fixing the mast, in the problem under consideration it is not possible to install piles. Therefore, the blocks are installed directly into the water and are not attached to the bottom by anything. Fixation occurs due to the force of friction between the block and the bottom of the reservoir and the force of gravity. Static equilibrium is considered at ultimate dynamic loads, which were specified in the problem statement.

1. Introduction
The problem of a reliable arrangement of various engineering and technical structures is urgent. There are a large number of various publications devoted to the construction and operation of structures [1-2], including on water [3], accounting for random wind loads [4], concrete properties [5-7] and methods of analysis of structures with elastic bonds [8-15], which are ropes, computer modeling of buildings and structures [16]. Based on the available information, we will propose a new solution to the new problem of fixing the mast with concrete blocks located at the bottom of the reservoir using cables.

2. Formulation of the problem
Let us investigate the fixation of a mast with a height \( h \) (Fig. 1) under the action of several types of loads. Let the tension force of the cable with the payload \( T_1 \) be applied to it. There is also an external random force \( F \), that acts on the cable and deflects it to the side. The concrete block, to which the cable is attached, fixing the mast with the tension force of the cable \( T_2 \), is located at the bottom of the reservoir and is completely submerged in water (Fig. 1). The coefficient of friction between the concrete block and the bottom of the reservoir is \( \mu \). The density of water and concrete is denoted respectively \( \rho_w \) and \( \rho_c \). The research objective is to determine the mass \( m \) of concrete blocks, the minimum angle between the cables connecting them \( \alpha \) and the shape of the block.
3. Model Description
Let us consider the layout of the forces applied to the mast, blocks and cables in projections onto three mutually perpendicular planes (Fig. 1). Between the masts (the second one is not shown in Fig. 1) a cable is stretched, which acts on the mast with a force, the projection of which on the coordinate axes are \( T_1 \) and \( F \). Force \( T_1 \) arises from the action of a cable stretched between the masts and imparting an external random force \( F \). The arrangement of concrete blocks that fix the position of the masts is considered symmetrical with respect to the masts, and when solving the problem, only one block with a mast may be considered. The forces of tension of cables between the mast and blocks are \( T_2 \) and \( T_3 \).

![Figure 1. Three types of mast fixation scheme with forces applied in it](image)

Each block is affected by the cable tension force, the Archimedes force, the support reaction force, the gravity force and the friction force. All of them are shown in Fig. 1.

In Fig. 1 cross-sections of model 1-1 and 2-2 are presented, which illustrate in detail the mechanical essence of the problem.

4 Simplifying Assumptions.
Let us introduce the following approximations into the model.

1. We assume that all dynamic loads are included in the total forces \( T_1 \) and \( F \), and are the upper bounds of the estimate of the maximum loads acting in the system, and it is possible to replace the problem of dynamics with a problem of statics.
2. We assume that all cables are attached to the mast at one point and all forces are applied at one point.
3. Friction in the contact zone obeys the Coulomb law for dry friction, since the block squeezes out water from the contact zone due to its own weight.
4. We assume that the height of the concrete blocks, taking into account its subsidence into the ground, is negligible in comparison with the height of the mast.

5 Building a solution

In order to solve the problem of determining the mass of a block, writing down the static equilibrium conditions for the system under consideration in Fig. 1, taking into account the applied forces, we obtain that the mass of one concrete block, provided that two weights are installed, will be equal to (1):

\[
m = \frac{F(1 + \mu \alpha \gamma) + T_1(1 + \mu \alpha \beta)}{2 \mu g (1 - \rho_w / \rho_c)}.
\]

(1)

Let us carry out numerical estimates of the obtained result.

Let us assume \( T_1 = 20 \text{ kN}, \) \( F = 10 \text{ kN}, \) \( \mu = 0.7, \) \( \rho_w = 1000 \text{ kg/m}^3, \) \( \rho_c = 2200 \text{ kg/m}^3, \) \( g = 9.81 \text{ m/s}^2, \) \( \beta = [\pi/10, \ldots, \pi/2, 1], \) \( \gamma = [\pi/10, \ldots, \pi/2, 1]. \)

Fig. 2 shows that the larger the installation angles, the less its mass. But physically, they cannot be significantly increased due to the increase in the length of the cable and the size of the entire structure. Therefore, the optimal value will be \( \beta = \gamma = \pi/3. \) Before this value, the mass decreases slightly, and after this value, the mass of the block begins to increase nonlinearly. With this value of the angles, the mass of one load will be \( m = 7435.54 \text{ kg} \approx 7.5 \text{ t.} \) This is the minimum value of the mass, taking into account the wind load, bottom unevenness, etc., it is better to take with a margin of > 10%.

The angle between the cables is geometrically determined by the formula (2):

\[
\alpha = 2\arctg(\cos(\beta) \tan(\gamma)).
\]

(2)

The graph of the dependence of the angle \( \alpha \) on the angles \( \beta \) and \( \gamma \) has the form shown in Fig. 3. This shows that the angle \( \gamma \) can be slightly reduced, for example, to \( \pi/4. \) Then the mass of the load will be \( m = 8.2 \text{ t.} \)

For values \( \beta = \gamma = \pi/3 \approx 1 \text{ rad.} \) angle \( \alpha \approx 82^\circ \)
For values \( \beta = \pi/3 \text{ rad.}, \gamma = \pi/4 \text{ rad.} \) angle \( \alpha \approx 53^\circ \)

Further minimization of the angle between the cables is associated with a significant increase in mass. Therefore, the minimum angle should be considered an angle of about 50°.
Let us determine the place of attachment of the cable to the block and its shape, providing resistance to overturning and the height of the block in relation to its length, at which it will not overturn (Fig. 4).

**Figure 4.** Block scheme and location of the cable attachment

The attachment point to the concrete block is the geometric center of its surface. In the case of a rectangular parallelepiped, this surface is a rectangle and its middle is the intersection point of the diagonals.

The block is installed along the direction of the cable projection onto the horizontal surface, φ is the angle between the cable and its projection onto the surface of the concrete block. Then (3):

$$\sin \phi = \frac{h}{l} \rightarrow \phi = \arcsin \left(\frac{h}{l}\right), \quad (3)$$

where: \(h\) is a mast height, \(l\) is a cable length: \(l = s/(2\sin(\alpha/2))\).

Geometry (4):

$$d = h \tan \beta, \quad s = 2htg\gamma. \quad (4)$$

The cable pulling force is estimated by the maximum value as follows (5):

$$T_2 = \sqrt{T_1^2 + F^2}. \quad (5)$$

Under the assumption that in the limiting state before overturning the reaction forces of the support and friction forces are applied to the front lower rib \(b\), we have (6) (see Fig. 4):

$$\frac{c}{a} \leq \frac{mg(1 - \rho_w / \rho_c) - T_2 \sin \phi}{2T_2 \cos \phi}. \quad (6)$$
6. Numerical estimates

Let us consider a numerical example.

For $\beta = \gamma = \pi/3 \approx 1$ rad. angle $\alpha \approx 82^\circ$, mast height $h = 15$ m. 

\[
\begin{align*}
  d &= h \tan \beta = 25.98 \text{ m} \approx 26 \text{ m}, \\
  s &= 2h \tan \gamma \approx 52 \text{ m} \quad \text{distance between blocks}, \\
  l &= s/(2\sin(\alpha/2)) = 39.7 \text{ m}, \\
  T_2 &= \sqrt{T_1^2 + F^2} = 22360 \text{ kN}, \\
  \varphi &= \arcsin(h/l) = 22.2^\circ, \\
  m &= 7435.54 \text{ kg}.
\end{align*}
\]

\[\frac{c}{a} \leq 0.77, \text{ i.e. block height } c \leq 0.77a \text{ from his length.}\]

Concrete block volume $V = m/\rho_e = 3.38 \text{ m}^3$.

Then, if we take the block thickness $b = c$ – its height, height $c = 0.77a$, from his length, then $V = 0.77^2 a^3 \rightarrow a = \frac{\sqrt[3]{V}}{0.77^2} = 1.79 \text{ m}$, then $b = c = 1.38 \text{ m}$.

Thus, the geometric dimensions of the concrete block in the form of a rectangular parallelepiped, which ensure its resistance to overturning, have been obtained.

7. Conclusion

The article is the first to propose a spatial model of the installation of the mast with fixing blocks located in the water. As a result of solving the problem, regularities in the arrangement of blocks were established, and numerical estimates of the mass of blocks were carried out. The simulation results can be used in the future to solve practical problems when installing such structures at energy facilities, cellular communications, sports and agricultural facilities.

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