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STABILITY OF FLOATING CRANES FOR LIFTING SUNKEN OBJECTS AND STEEL PILES

***Rade VASILJEVIĆ*[1]**

[1)] *School of Railroad Transport, Academy of Technical and Art Applied Studies*

ORCID iDs:Rade VASILJEVIĆ https://orcid.org/0000-0003-0458-8545

Abstract

This paper analyzes the stability parameters of floating cranes in the process of lifting sunken objects (e.g. floating objects) on inland waterways and lifting steel piles or vibro hammers. The stability of the floating crane is studied through the structural stability of the floating cranes and the stability of the whole machine. The focus of the floating crane stability analysis is the influencing parameters: lifting weight, wind load, angles of inclination of the pontoon, and the others.

Keywords*: floating cranes, sunken objects, steel piles, influnce parameters, stability.*

1 INTRODUCTION

Floating cranes are floating transport machines, which consist of from the floating part (pontoon) and crane (boom). Different constructions of floating cranes were made.The most common type is with a fixed column and a movableboom. Basic mechanisms of the floating cranes are:the mechanism for lifting and lowering load and the mechanism for slewing the crane. They are used forlifting sunken objects (e.g. ships, parts of ruinousedbridges, ...) and duringbuilding in and on the water (e.g. dams of steel piless, ...). Sunken objects represent obstacles that endanger navigation[1]. These objects influence the reduction of the width and depth of the waterway, thus that there may be an endanger navigation.How sunken objects very seriously threaten the safety of navigation that is their removal must be approached seriously and thoroughly.With on the other hand, sunken objects also represent potential hazard to the natural environment.For lifting sunken objects mostly floating cranes are used.It is shown in Fig. 1 a floating crane in the execution of a lifting transport operation sunken ship.They can be used to lifting a sunken ship use two or more cranes [2].Salvaging the sunken objects to the coast is carried out using other transport equipment (e.g. winch, ...).

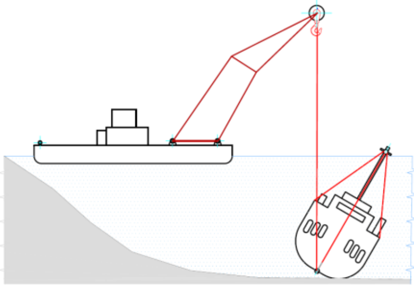

Fig. 1*Transport operation of lifting a sunken ship with a floating crane*

Floating cranes find an important application in execution as well the transport operation of lifting steel piles for technology of making dams from steel piless (Fig. 2). A floating crane is placed above the floating object used to deliver the pallets, a pair of piles is hung and lifted to the required [3, 4]. By laving, the object is brought to the axis of the previously placed ones the leader and the group are healed with the help of the staff placed in the basket in previously set.Then the pileslowered. Leaders keep the direction of the dams. The piles are driven in with auxiliary mechanization. The procedure is repeated.

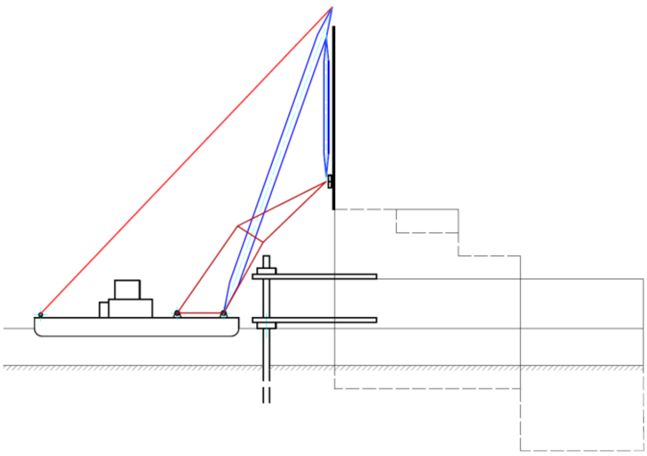

Fig. 2*Transport operation of lifting steel piles with a floating crane*

In the paper, the accent is placed on the stability of floating cranes when lifting floating objects.

2 CARRYING CAPACITY AND LOAD ANALYSIS

The carrying capacity of the floating crane for lifting sunken objects is determined from the following conditions:

$$W_c > G_c + G_o + G_p \tag{1}$$

where are:

- $W_c(kN)$ – the required crane displacement,
- $G_c(kN)$ – the whole weight of the crane,
- $G_o(kN)$ – the whole weight of the object lifting from the bottom,
- $G_o(kN)$ – the force of separating the sunken object from the river sediment.

The loads acting on the crane can be static and dynamic [5]. Static loads are: the load of the crane when lifting the load and the force of constant wind. Dynamic loads are: sudden impact loads (e.g. due to breaking of the rope when lifting the loads, ...), the force of sudden wind impact and the dynamic force of waves. With a floating crane, there are main, additional and special loads.

2.1 Main loads

The main (permanent) loads of the floating crane of a type in [3](see Figs. 1 and 2) are:

- $F_{Q1}(kN)$ – the load from the payload on the top of the boom,
- $F_{Q2}(kN)$ – the load from the useful load on the breakage of the axis of the catarrh,
- $G_1(kN)$ – the force from its own weight on thetop of the boom,
- $G_2(kN)$ – self-weight force at the break of the shaft of the boom structure.

At the same time, both devices for lifting load never work.The force from its own weight on the topof the boom G_1includes the weight of the gripping device (e.g. hooks), reel and other moving parts. The force from own weight on the break of the arrow shaftG_2includes the weight of the own structure of the boom, hook, reel and other moving parts.

For the calculation, the position of the boom of the floating crane is taken as normal to the longitudinal centerline of the pontoon. In the case of floating cranes with a non-slewing boom (the boom is operated in the longitudinal plane), the possible existence of an asymmetric load on the gripping devices (e.g. hooks, ...) must be taken into account.

Further, for the calculation, the position of the center of gravity of the load on the hook must be taken to be at the point of grip of the hook on the construction of the crane boom.Contingent upon on the construction of the floating crane, the main loads may also include the weight of permanent counterweights. In the calculations, the own weight of moving parts (e.g. hooks, grippingdevice, …) can be ignored, if their weight does not exceed 5% of the weight of the lifted load.

2.2 Additional loads

Additional loads are:

- $F_v(kN)$– the wind force,
- $F_w(kN)$ – thedynamic force of waves.

Wind load$F_v$is the force acting on the structure of the boom of the floating crane. The magnitude of the wind force is influenceby wind speed, wind density, surface area of the boom structureof the floatingcrane and wind direction. The wind force can be calculated using the appropriate formula. See Eq. (2).

$$F_v = c \cdot q \cdot A_v \tag{2}$$

where are:

- c– the shape coefficient of the surface of the boom structure affected by the wind[6],
- $q\ (N/mm^2)$ – the wind pressure (for wind speed$v_v \leq 20\ m/s$is$q = 250\ N/mm^2$, and for higher speeds, when operation is prohibited, see[6]),
- $A_v(mm^2)$– the surface of the boom structure exposed to the wind.

The dynamic wave force$F_w$is the force acting on the base of the floating crane (pontoon). When working at sea, the impact force of the waves and swaying in the horizontal direction influence the stability of the crane. The wave force can be calculated using the formula:

$$F_w = c_w \cdot H_w \cdot \rho \cdot g \cdot A_p \tag{3}$$

where are:

- c_w– the wave impact coefficient (depending on the characteristics of the waves and the structure of the pontoon),
- $H_w(mm)$ – the height of the waves,
- $\rho\ (kg/m^3)$ – the density of water,
- $g\ (m/s^2)$ – the acceleration of gravity,
- $A_p\ (mm^2)$ – thearea of the ponton base in contact with the water.

2.3 Special loads

Special loads include: test loads, structural loads (contingent upon on the applied method of mounting the load device and the technology of the assembly operations), the impact of wave repulsion and breaking off the load.In the case of an accident (fall - breaking off the load from the hook), the stability must be checked for the most unfavorable loading condition with the load on the hook, taking into account the possible asymmetric distribution of the load on the shipboard [8].

3 STABILITY OF FLOATING CRANE - GENERAL CONSIDERATIONS

The floating crane must be structured in such a way that it can resist swivelling of the pontoon due to the action of external forces. In other words, it must have sufficient stability.In general, the stability of a floating crane consists of two levels, as follows:

- the stability of the boomstructure, and
- the stability of the pontoon.

The structural stability of the boom refers to the steel structure of the boom under all external loads, resistance to pressure, warping and destabilization, as well as the ability to continue working.

The stability of the pontoon refers to the stability of the floating crane anti-overturning.The floating crane, after assembly and installation, must be tested under the maximum external load and various unfavorable conditions.

When the floating crane is in working condition, then the lifting weight, wind speed and direction are constantly changing, and the angle of slope of the pontoon is not fixed.Therefore, when calculating the stability of a floating crane, it is necessary to take into account all working conditions and calculate the relevant stability.

According to force analysis, static and dynamic stability are differented.According to the stability conditions, with the static load of the crane, in the normal case of the drive, the pontoon slope angles must be less than or equal to the predetermined value (mainly 5°).In the case of static loading (small angles of slope of the pontoon), it is sufficient to use formulas for initial stability.The calculation of stability must also include the stability of the crane in the case of an accident (e.g. when a dynamic load occurs in emergency

cases).In the case of dynamic loading, the diagram of static stability lever and the diagram of reduced wind moment are used, so that the slope angles are obtained by equalizing the corresponding areas under those curves[7].
The angle of slope of the crane when lifting the load must be limited because the reach of the crane boom depends on it.A greater change in reach of the boom can be realized even at low angles of slope due to the high suspension height of the hook for lifting the load.The load of the crane is determined by the load moment, which is equal to the product of the weight of the load and the reach of the crane boom.For floating cranes, the height of the load suspension is also important, because the higher the height, the lower the initial stability of the pontoon and the angle of slopeis greater when lifting the same load.If the dimensions of the pontoon are limited, normal building cannot be applied.
If the sea-gauge of the pontoon is limited and the length and width are not (floating crane operating on rivers or close to shore in natural harbors), the crane will have a horizontal bottom to make full use of the sea-gauge.With a sloping bottom, the bottom comes out of the water even at small slopes, which significantly reduces stability.Fixed counterweights are used for the aim of simple construction and lowering the center of gravity of the system.The lower efficiency of fixed counterweights can be compensated by the greater width of the pontoon, which significantly increases stability.If the sea-gauge and width of the pontoon are limited at the same time (cranes working in channels), then the use of movable counterweights is required to improve the stability of the crane.If counterweights are placed on the rails of the swivel top device, then the center of gravity of the system is lifted, which causes a decrease in stability.
Furthermore, stability can be compensated by increasing the waterline area.Forasmuch as width is limited, this can only be achieved by increasing the length of the pontoon.Increasing the length of the pontoon is not practical because it is difficult to maneuver such a crane.A better solution is to place the movable counterweight lower (on the pontoon), which only a partial load balance.In this case, the counterweights are also ballast for balancing the pontoon in the longitudinal direction.If the width of the pontoon is so limited that a fixed counterweight crane cannot be applied, and the sea-gauge is not restricted, then the payload can be completely counterbalanced.This solution slightly affects the increase of the displacement, so it is not necessary to increase the main dimensions of the pontoon because by suitable shaping of its underwater form (slanted bottom islifted towards the stern), the center of gravity of the displacement can be moved towards the stem.This means that in the longitudinal direction the crane can be balanced even without ballast.A small sea-gauge at the stern of the pontoon is not a problem, because the crane works without slope, but you should pay attention to the possibility of the crane overturning over in case of breaking the rope for lifting the load.
Moving the center of gravity of the displacement towards the stem is not appropriate, because the ballast is reduced.At the maximum given width of the pontoon, the metacenter height is reduced, which is not allowed for floating cranes.
The unsinkability calculation should provide that in the case of water penetration, due to the load on the pontoon's outer panel, the overturning or engulfment of the floating crane should be prevented.The unsinkability of the floating crane (similar to ships) is achieved by aappropriatelayout of longitudinal and lateralhermetically partitions inside thepontoon and a determinate size of the above water.When calculating the unsinkability, two cases are assumed that the pontoon deck does not sink under water, as follows: 1. if the hook is unloaded, then two adjacent sections - spaces can be washed ashore, and 2.if the hook is loaded,then only one section can be washed ashore without the pontoon shipboard being submerged under water [7].
The floating crane during navigation, moving within the work area and in all conditions without a load on the hook,must meet all requirements for the stability of the pontoon with the surface exposed to the wind calculated by the method of calculating the action on high structures of complexshape.

4 INFLUENCE OF LOAD ON STABILITY

The main influencing parameter on the stability of the floating crane is the suspended load, the knowledge of which is particularly important. The influence of the load on the stability of the floating crane is determined according to two criteria, as follows:

- basiccriteria, and
- additional criteria.

4.1 Basiccriteria

The longitudinal and lateral stability of the floating crane is checked using the basic criteria. To that aim, Fig. 3 and Fig. 4 show the models of the influence of the suspended load on the stability of the floating crane in the longitudinal and lateral directions.

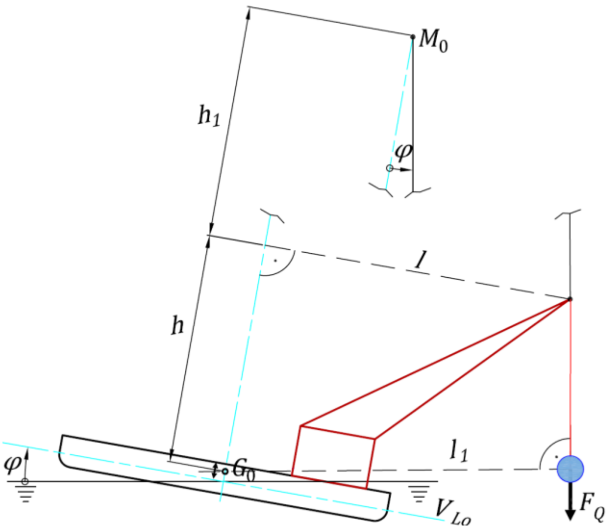

Fig. 3*Model of the influence of the suspended load on the stability of the floating crane in the longitudinal direction*

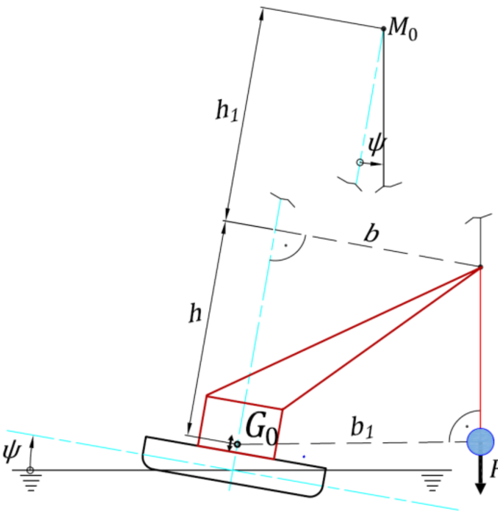

Fig. 4*Model of the influence of the suspended load on the stability of the floating crane in the lateral direction*

When the load hangs on the grabble device of the boom (e.g. hook, ...) of the floating crane, then its stability will be reduced, so that the pontoon of the crane will tilt in the longitudinal direction by an angle$\varphi$and in the lateral direction by an angleψ. So, for the lifting capacity$m_Q$of the floating crane, the reduction of the initial metacenter height, the angle of longitudinal slopeφ, the angle of lateralslope$\psi$and the total change of trim$u$ must be determined.One approach to determining these parameters is given in[9].

With an increase in the load$F_Q$at a determinned height, there is a displacement in the weight of the floating crane system(new$\overline{M_0G_1}$). The height of the load corresponds to the height of the axle of the upper reel of the self-propelledcrane above the center of gravity of the floating cranesystem$h$.

A decrease in stability is equal to a decrease in the initial metacenter height:

$$\overline{G_0G_1} = \frac{F_Q \cdot h}{D+F_Q} \tag{4}$$

where are:

- h – load suspension height measured from the center of gravity of the systemG_0,
- D –displacement of the considered state.

The new initial metacenter height is determined using the formula:

$$\overline{M_0G_1} = \overline{M_0G_0} - \overline{G_0G_1} \tag{5}$$

When the floating crane slope in the longitudinal direction by the angle φ(Fig. 3) or in the lateral direction by the angleψ (Fig. 4), when lifting the load, then the slope moment lever$l_1$or$b_1$is equal to:

$$l_1 = (h + h_1) \sin\varphi \tag{6a}$$

$$b_1 = (h + h_1) \sin\psi \tag{6b}$$

where$h_1$is the distance from height$h$to the point of intersection of the direction of action of buoyancy for the water line$VL_0$with the direction of action of loadF_Q.

The stability equations in the longitudinal and lateral directions read:

$$F_Q \cdot l_1 = (D + F_Q) \cdot \overline{M_0G_0} \cdot \sin\varphi \tag{7a}$$

$$F_Q \cdot b_1 = (D + F_Q) \cdot \overline{M_0G_0} \cdot \sin\psi \tag{7b}$$

orin the form:

$$F_Q \cdot (h + h_1) \cdot \sin\varphi = (D + F_Q) \cdot \overline{M_0G_0} \cdot \sin\varphi \tag{8a}$$

$$F_Q \cdot (h + h_1) \cdot \sin\psi = (D + F_Q) \cdot \overline{M_0G_0} \cdot \sin\psi \tag{8b}$$

orin thebetter form:

$$F_Q \cdot (h + h_1) = (D + F_Q) \cdot \overline{M_0G_0} \tag{9a}$$

$$F_Q \cdot (h + h_1) = (D + F_Q) \cdot \overline{M_0G_0} \tag{9b}$$

If$l$is the horizontal distance of the attack force$F_Q$from the water line and$b$is the distance of the center of gravity of the suspended load from the centerline of the plane of the floating crane system, then$h_1$in the horizontal position of the crane is equal to:

$$h_1 = l \cdot \cot\varphi = \frac{l}{tan\varphi} \tag{10a}$$

$$h_1 = b \cdot \cot\psi = \frac{l}{tan\psi} \tag{10b}$$

Substituting expressions (10a) and (10b) in equations (9a) and (9b) obtains:

$$F_Q \cdot (h + \frac{l}{tan\varphi}) = (D + F_Q) \cdot \overline{M_0G_0} \tag{11a}$$

$$F_Q \cdot (h + \frac{l}{tan\psi}) = (D + F_Q) \cdot \overline{M_0G_0} \tag{11b}$$

orin the still betterform:

$$F_Q \cdot h + F_Q \cdot \frac{l}{tan\varphi} = (D + F_Q) \cdot \overline{M_0G_0} \tag{12a}$$

$$F_Q \cdot h + F_Q \cdot \frac{l}{tan\psi} = (D + F_Q) \cdot \overline{M_0G_0} \tag{12b}$$

Further transformation of equations (12a) and (12b)obtains:

$$F_Q \cdot h \cdot tan\varphi + F_Q \cdot l = (D + F_Q) \cdot \overline{M_0G_0} \cdot tan\varphi \tag{13a}$$

$$F_Q \cdot h \cdot tan\psi + F_Q \cdot l = (D + F_Q) \cdot \overline{M_0G_0} \cdot tan\psi \tag{13b}$$

orin the finally form:

$$F_Q \cdot l = (D + F_Q) \cdot \overline{M_0G_0} \cdot tan\varphi - F_Q \cdot h \cdot tan\varphi \tag{14a}$$

$$F_Q \cdot l = (D + F_Q) \cdot \overline{M_0G_0} \cdot tan\psi - F_Q \cdot h \cdot tan\psi \tag{14b}$$

Finally, the angles of longitudinal and lateralslope of the floating crane systemφandψread:

$$tan\varphi = \frac{F_Q \cdot l}{(D+F_Q) \cdot \overline{M_0G_0} - F_Q \cdot h} \tag{15a}$$

$$tan\psi = \frac{F_Q \cdot b}{(D+F_Q) \cdot \overline{M_0G_0} - F_Q \cdot h} \tag{15b}$$

On basis the angle of longitudinal slope of the floating crane system:

$$\frac{u}{L} = tan\varphi \tag{16}$$

the total trim change is equal:

$$u = \frac{F_Q \cdot l \cdot L}{(D+F_Q) \cdot \overline{M_0G_0} - F_Q \cdot h} \tag{17}$$

4.2 Additional stability criteria

Additional stability criteria of the floating crane must be met for two cases, as follows:

- the case of lifting the load,and
- the case of a sudden drop of the load.

The stability is checked for the maximum carrying capacity of the grabble device of the crane and the most unfavorable case of lifting the load in the most unfavorable condition of loading.

i. The first additional stability criterion - the case of lifting the load. Fig. 5 shows the model of the influence of lifting the load on the stability of the floating crane.

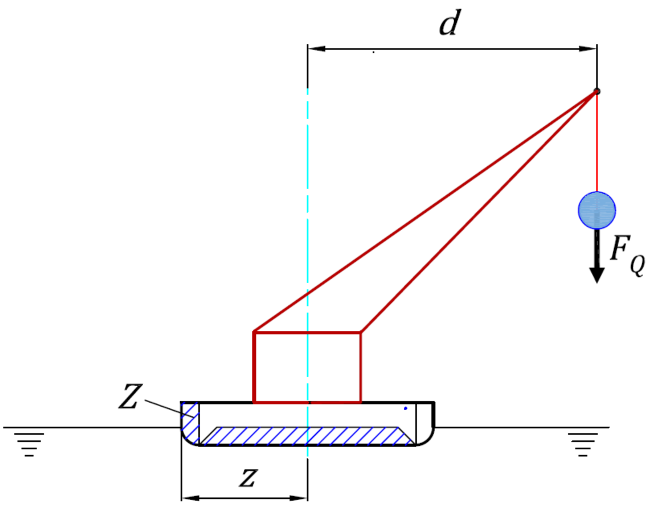

Fig. 5*Model of the influence of lifting the load on the stability of the floating crane*

The notations in Fig. 5 are as follows:

- m_Q– mass of the load, which is lifted,
- d–transverse distance between the load and the longitudinal symmetrical plane,
- Z– mass of ballast, which is used to level the pontoon (if used),
- z– transverse distance between the center of gravity Z of the ballast and the longitudinal symmetrical plane.

Fig. 6 shows a diagram of stability levers when lifting loads [10].

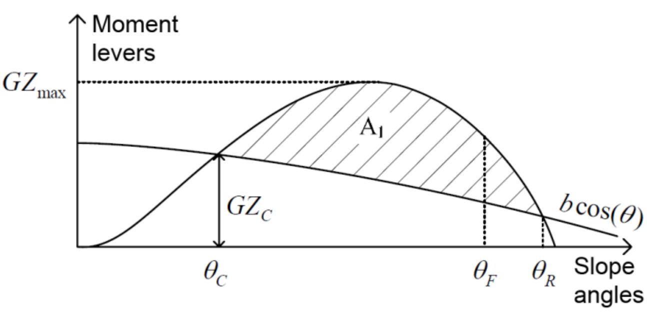

Fig. 6*Diagram of stability levers when lifting loads [10]*

The notations in Fig. 6 are as follows:

- θ_C– equilibrium slope angle (corresponds to the first intersection point of the stability lever curve and the slope lever curve),
- θ_R– angle of loss of stability (corresponds to the second intersection point of the curve of the stability lever and the curve of the slope lever),
- θ_F– angle of inundation (at this angle there is immersion of unprotected openings),
- A_1– the area between the curve of the stability levers and the curve of the tilt levers (measured from the tilt angle$\theta_1$to the tilt angleθ_2).

The first additional stability criteria (18a)-(18c) [10]must be met during the lifting of the load by the floating crane:

$$\theta_c < 15° \tag{18a}$$

$$G \cdot Z_c \leq G \cdot Z_{max} \tag{18b}$$

$$A_1 \geq 0{,}4 \cdot A_{tot} \tag{18c}$$

The notationA_{tot}in expression (18c) is the total area under the curve of stability levers.

In the first additional stability criterion (18a)-(18c), the slope lever due to lifting the load is obtained by the following formula:

$$l_a = m_Q \cdot d - \frac{Z \cdot z}{D} \tag{19}$$

where$D$is the displacement of the considered state.

ii. The second additional criterion of stability - the case of a sudden drop of the load. The case of a sudden load drop is considered by assuming a load drop due to the breaking of the steel rope for lifting. For dat aim, Fig. 7 shows a model of the influence of a sudden drop of load on the stability of the floating crane.

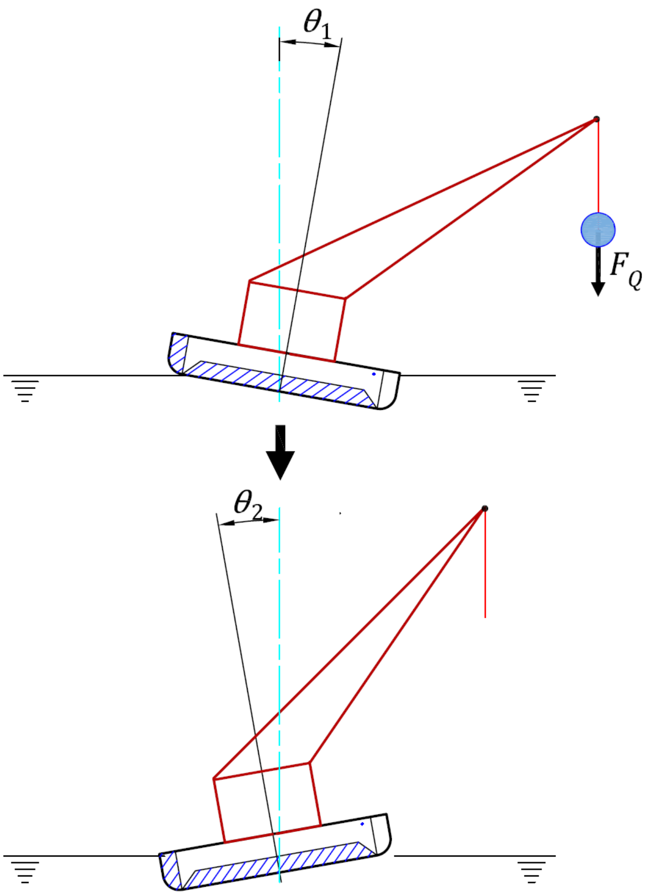

Fig. 7*Model of the influence of a sudden drop of load on the stability of the floating crane*

The notations in Fig. 7 are as follows:

- m_Q– mass of the load, which lifting and sudden drop,
- θ_1– equilibrium angle of slope during load lifting,
- θ_2– inundation angle (do not take more than 30°; at this angle, subjects on the deck move),

Fig. 8 shows a diagram of stability levers in in case of sudden load drop[10].

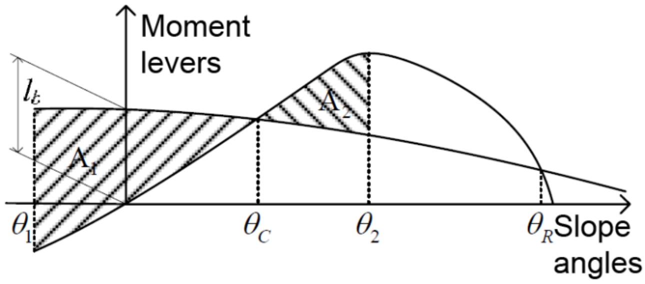

Fig. 8*Diagram of stability levers in case of sudden load drop [10]*

The notations in Fig. 8 are as follows:

- θ_C– equilibrium slope angle (corresponds to the first intersection point of the stability lever curve and the slope lever curve),
- θ_R– angle of loss of stability (corresponds to the second intersection point of the curve of the stability lever and the curve of the slope lever),
- A_1– the area between the curve of the stability levers and the curve of the slope levers (measured from the angle of slope$\theta_1$to the angle of slopeθ_2),
- A_2– the area between the curve of the stability levers and the curve of the slope levers (measured from the angle of slope$\theta_C$to the angle of slopeθ_2).

In the case of a sudden drop of the load during the lifting of the load with a floating crane, according to [10] the second additional criterion of stability must be met:

$$\frac{A_2}{A_1} \geq 1 \tag{20a}$$

$$\theta_R - \theta_2 \geq 20° \tag{20b}$$

In the second additional stability criterion (20a)-(20b), the slope lever due to drop load is obtained by the following formula:

$$l_b = Z \cdot \frac{z}{D} \cdot \cos\theta \tag{21}$$

5 CONCLUSION

For the use of floating cranes for transport operations (e.g. lifting sunken objects, lifting steel piles, ...) it is necessary to carry out stability calculations and determine the conditions for each specific lifting operation. In the paper, the accent is placed on the influence of the suspended load on the stability of the floating crane. In other words, the influence of the suspended load on longitudinal stability and lateral stability was demonstrated. The influential parameters were determined, as followslongitudinal slope and lateral slope. It has been shown that the influence of suspended loads can be significant and hasardous. It was indicated that valid calculations are very important for the successful execution of the transport operation, on the one hand, and for the safety of the crew and rigging, on the other hand.

The technical development of floating cranes for cargo handling with faster and safer cargo handling requires further development of dynamic models of floating cranes. In this sense, this paper leaves room for the author to continue researching the stability of floating cranes in the direction of the possible formation and solution of new dynamic models.

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Contact address:
RadeVasiljević
Academy of Technical and Art Applied Studies in Belgrade
School of Railroad Transport
11000 Belgrade
Z. Čelara 14
E-mail: rade.vasiljevic@vzs.edu.rs