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ANALYSIS OF THE POSSIBILITIES OF UNDERWATER CROSSING BY THE MG-20 ASSAULT BRIDGE

Abstract. The article presents an analysis of the possibilities and limitations associated with negotiating a deep water obstacle on its bottom by the MG-20 assault bridge on tracked chassis. Various options for deep fording are analyzed and assessed: with the bridge span set on the chassis, with the bridge span raised, with the bridge span towed and with the bridge span submerged. Recommendations for future tests are set forth.

Keywords: assault bridges, support bridges, underwater crossing.

1. INTRODUCTION

Assault bridges on tracked chassis accompany armoured units during troop movements and combat operations. Therefore their mobility should not significantly differ from that of other mechanized vehicles, including: tanks, personnel carriers, self-propelled guns, etc. Tactical and technical requirements placed on bridges in terms of speed of movement, ballistic shields, negotiating obstacles, including fords, are very similar to the requirements placed on combat vehicles.

Deep water obstacle means one with a depth of up to 5 m, length of 1000 m, bank slopes on entry and exit up to 30% grade. The assumed flow velocity is up to 2 m/s. Bearing capacity of the bed is not defined.

Heavy armoured equipment can negotiate such an obstacle by crossing a bridge, on a ferry, with the help of special floats or on its own - by moving on the bed of the obstacle, which is the subject of this article.

The requirements for an assault bridge specify that it should be able to negotiate obstacles on the bed of the obstacle like a tank. It follows from this that the time to prepare the bridge for crossing, and the time of the crossing itself, should not deviate significantly from the time assumed for a tank.

Difference in dimensions and weight between an assault bridge which carries a bridge span and armoured vehicles is the basic difficulty in effecting obstacle crossing by the bridge on the bed of a deep water obstacle.

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2. MG-20 BRIDGE CHARACTERISTICS AND EFFECT THEREOF ON THE SUBMERGED VEHICLE

2.1. Weight and displacement data of the MG-20 bridge

The MG-20 assault bridge consists of base chassis PMG-20, based on PT-91 tank, and bridge span PM-20 (Fig. 1).

Fig 1. MG-20 bridge

Product weight:	57,000 kg (chassis 42,000 kg, span 15,000 kg)
Maximum approach angle:	30°
Displacement force:	440 kN (chassis 216 kN, span 224 kN)
Apparent weight of submerged bridge:	119 kN

Coordinates of the centre of gravity of chassis and span: Figs. 2 and 3

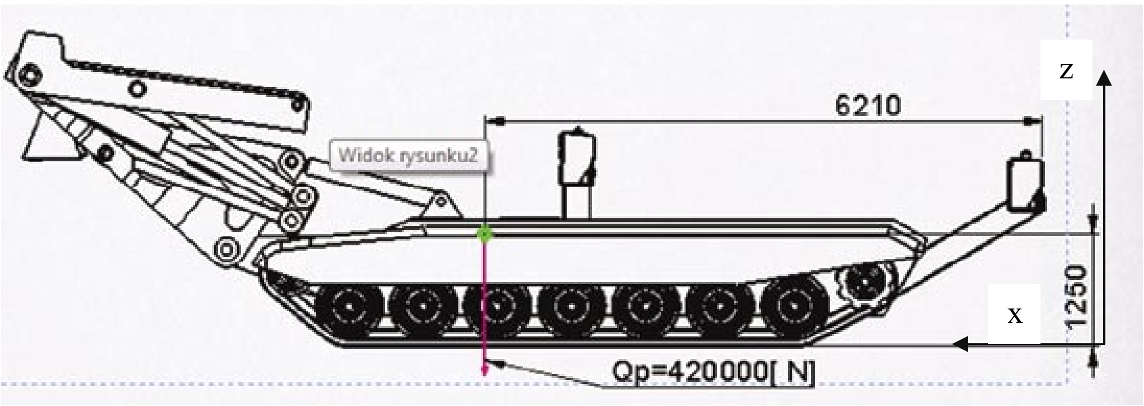

Fig. 2. Coordinates of the centre of gravity of the chassis

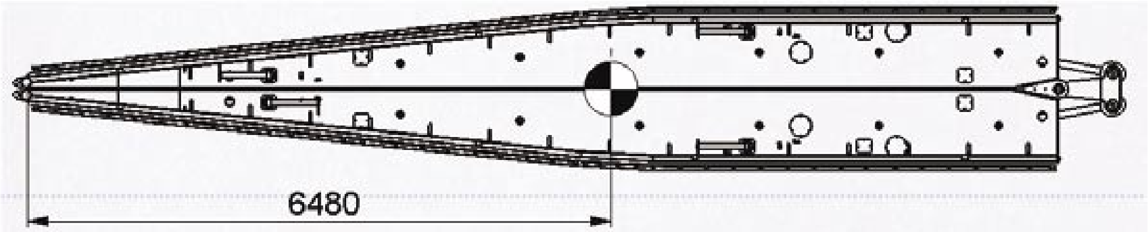

Fig. 3. Coordinates of the centre of gravity of the span

The coordinates of the centre of gravity of the chassis in the coordinate system shown in Fig. 2 crossing the centre of symmetry of the vehicle are as follows:

$x_c = 6210$ mm, $y_c = 39.5$ mm, $z_c = 1250$ mm [2].

Lateral surface area of chassis:	14.14 m^2
Front surface area:	9.84 m^2
Displacement of chassis:	22.05 m^3
For the span (Fig. 3)	$x_c = 6480$ mm,
Lateral surface area of span:	16.85 m^2
Front surface area of span:	5.55 m^2
Displacement of span:	22.8 m^3.

Fig. 4. Determination of chassis displacement force [2]

2.2. Forces acting on submerged vehicle

The following forces act on a submerged moving vehicle (Fig. 5):

force of gravity	G,
displacement force	W,
side thrust (from current)	Fb,
drag force of water	Fc,
tractive resistance	R,
ground reaction force.	

These forces are applied in defined locations:

- force of gravity G: in the centre of gravity of the set, directed along the z^+ axis;
- displacement force W: in the centre of displacement, directed along the z^- axis;
- side thrust Fb: in the centre of side surface, directed along the y^+ axis, calculated for flow velocity of 2 m/s;
- drag force of water Fc: in the centre of front surface, directed along the x^- axis, calculated for flow velocity of 2 m/s;
- tractive resistance at the level of bed, directed directed along the x^- axis;
- ground reaction force (consisting of three components: along axes x, y and z). The component force along the x axis is the driving force P. The component force along the y axis counterbalances the side thrust Fb. These reaction forces are limited by ground adhesion. The vertical component, along the z axis, counterbalances the apparent weight of the vehicle.

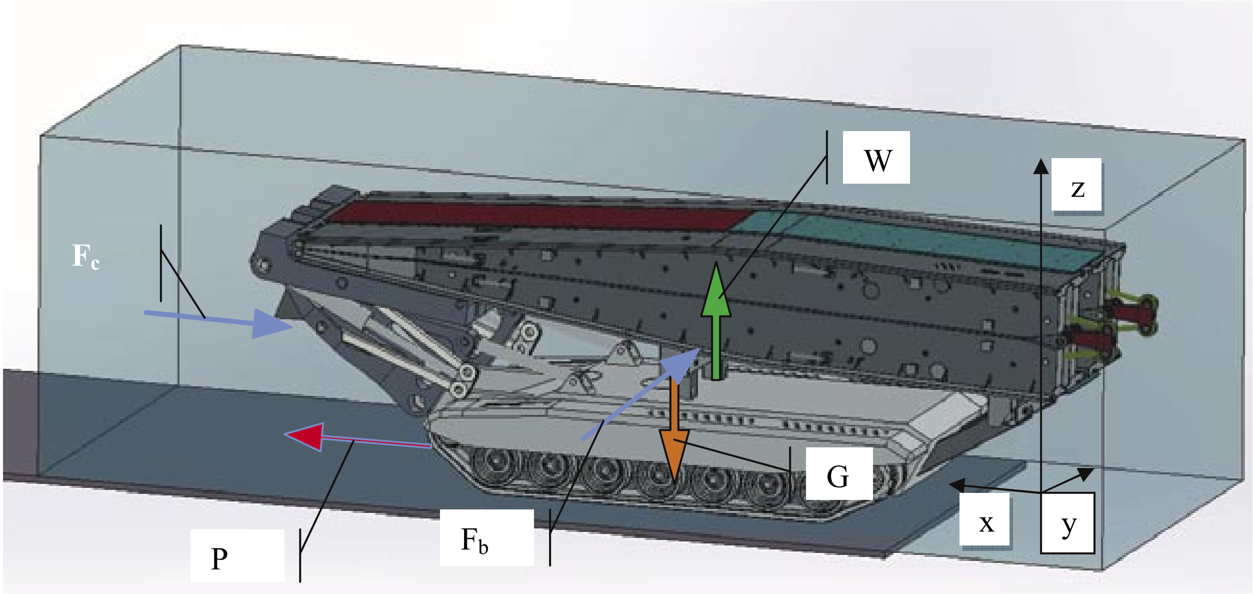

Fig. 5. Forces acting on submerged vehicle

Due to the complex design of the vehicle and the difficulty in accurately modelling the tractive resistance, the values and directions of these forces were adopted based on an estimation. The coordinates of the points of application of individual forces and their values are listed in Table no. 1 based on [1] and [2].

Table 1. Forces acting on a submerged vehicle.

Force	Symbol	Value (kN)	Coordinates		
			x	y	z
Weight	G	559	5421	22	1595
Displacement	W	440	4867	0	2337
Side thrust	Fb	73.2	5163	0	2162
Front drag force	Fc	35.8	12500	0	2000

The coordinate system is associated with the ground (x and y axes), whereas the origin of the system is aligned with the symmetry axis of the vehicle and the z axis passes vertically from the ground level through the edge of the rear support beam of the span. The x-axis is directed to the front of the vehicle, the y-axis is perpendicular to the possible direction of vehicle movement (see Figs. 2 and 5).

The force of apparent weight is the difference between the force of weight and displacement. In the case of a freely floating body, the line of force of apparent weight is a vertical line passing through the centre of gravity (and centre of buoyancy). Where the lines of the forces of displacement and gravity do not coincide (but are parallel) a moment is created that rotates the object to a position where the lines of action of the two forces become aligned. If the immersion depth is too small and the object can not take that position, then the object partially emerges and changes its position in water, so that both lines of force, of the changed displacement and of the weight, become aligned.

The side thrust depends on the lateral surface and on the flow velocity. Assuming the flow velocity of 2 m/s and the lateral surface area of 31.1 m^2, the thrust force was estimated at 73.2 kN and applied in the geometric centre of the lateral surface. The front drag was estimated similarly to the side thrust: with the front surface area of 15.4 m^2 and a driving speed of 2 m/s, the value of 35.5 kN was obtained.

Tractive resistance is difficult to evaluate; it was assumed that it depends on the type of ground, consequently on the rolling resistance coefficient f. Table 3 lists the resistance coefficients for several types of ground, but they all refer to open air conditions, rather than water. For the purpose of comparing the various crossing methods, one value f = 0.1 (wet sand) was adopted. Climbing resistance (when leaving ford) depend on the grade of exit. It is calculated in a similar way to rolling resistance, whereas the resistance coefficient is the tangent of the climbing angle (requirements specify the max. value of 0.3 - the exit angle may be up to 30%).

Friction (ground adhesion) should counterbalance the side thrust and provide the driving force P necessary to overcome front drag and tractive resistance. Its maximum value is limited by the friction (adhesion) coefficient between the tracks and ground. It was estimated on the basis of literature data [5]. Examples of the value of friction coefficient are given in Table 2.

Table 2. Coefficient of adhesion to ground μ [5]

Ground type	Adhesion coefficient μ
Asphalt	0.75 - 0.80
Dry meadow	1.04
Mud	0.35 - 0.4
Loose snow	0.2
Sand	0.4 - 0.7

Table 3. Rolling coefficient f

Ground type	Tractive resistance coefficient
Asphalt	0.03 - 0.06
Meadow with mown grass	0.08
Muddy dirt road (moisture 20%)	0.12 - 0.15
Stubble field	0.07 - 0.08
Wet sand	0.1

2.3. Assessment of the ability to negotiate water obstacle fully submerged, together with bridge span

The first condition that must be satisfied in case of underwater crossing is that the apparent weight G', calculated as the difference between vehicle weight and its displacement, be positive. In the case discussed, that condition is satisfied: apparent weight is 119 kN.

The lines of displacement force W and weight G do not coincide. While due to the symmetry of the product the "y" coordinates of both centres are practically the same, there are, however, differences in the "x" coordinates. Therefore the rear of the vehicle will be raised and the there will be additional load on the front of the moving vehicle, which is also suggested by tests carried out by the Military Institute of Armoured and Automotive Technology (WITPiS) as part of the MG-20 qualification tests (Fig.6) [2]. The "x" coordinate of the displacement force does not coincide with the "x" coordinate of gravity, and is offset therefrom to the rear by ca. 160 mm.

The observed raising of the back of the vehicle is only partially due to the shift of the centre of buoyancy relative to the centre of gravity. Since the apparent weight of the bridge is only 119 kN, with the real weight being 559 kN, then, while the vehicle is submerged, the suspension of the vehicle raises the whole vehicle and the test, at a depth not much greater than the vehicle height (4 m), does not allow to determine the angle at which the submerged vehicle is positioned and whether there is indeed partial detachment of tracks from the ground.

In the case of standing water, when the bottom of the obstacle is flat, the crossing seems to be theoretically possible (tests carried out so far have not provided an unambiguous answer).

In the case of water flowing at the speed of 2m/s, the lateral thrust calculated in [1] is 73.2 kN, which is a value comparable with the pressure exerted by the vehicle on the ground.

The difference between the "x" coordinates of the centre of side thrust and the centre of ground pressure ($\Delta = 258 + 162$ mm) results in creating a moment that rotates the back of the vehicle in accordance with the direction of water flow. The value of the moment is 31 kNm. There is therefore a risk of turning the back of the vehicle with the water current, as the adhesion of the tracks to the ground may not provide sufficient counteracting moment of force.

The side thrust is another source of creating a moment of force (152 kNm) which acts to turn the vehicle over. The balancing moment (resulting from the apparent weight) is higher (180 kNm), but the surplus is only 20%.

The climbing resistance, rolling resistance and front drag act in the same direction. To overcome those forces of resistance the adhesion between tracks and the bottom of the obstacle should be higher than the total resultant resistance force. Assuming that the pressure on the ground is equal to the apparent weight (G – W), the minimum value of the coefficient of ground adhesion μ for crossing standing water is as follows:

- for overcoming front drag: $\mu_{boundary} > 0.30$
- for moving on flat bed: $\mu_{boundary} > 0.3 + 0.1 = 0.4$
- for exiting the ford: $\mu_{boundary} > 0.3 + 0.1 + 0.3 = 0.7$.

In order to take into account the need to balance side thrust, it is necessary to geometrically add to $\mu_{boundary}$ the friction component necessary to overcome the side thrust $\mu_b > 0.46$. The final boundary adhesion coefficients should be as follows: 0.55 – 0.61 and 0.84, respectively.

These values are high and, as follows from Table 2, there is no ground that meets this condition. Paved or sandy surface enables driving on the bottom. The conditions are not satisfied when exiting the ford. Only decreasing the vehicle speed (e.g. from 2 m/s to 1m/s) will relieve the requirements for $\mu_{boundary}$ during ford exiting to 0.66.

The conclusion is that the passage on the bottom of the obstacle by the bridge span on the vehicle chassis could be possible in standing water if that bottom was paved or sandy. If the transverse water flow velocity is 2 m/s, the crossing is assessed as risky. In addition, the vehicle speed would have to be reduced when exiting the ford in order to reduce tractive resistance and front drag.

Fig. 6. MG-20 testing at WITPiS [2]

Fig. 7. Raising of the back part of the bridge [2]

2.4. Assessment of the ability to negotiate water obstacle fully submerged, with raised bridge span

To ensure full crossing capabilities the side thrust should be reduced and the apparent weight of the vehicle should be increased. Both these conditions are satisfied when crossing is effected with the bridge span raised.

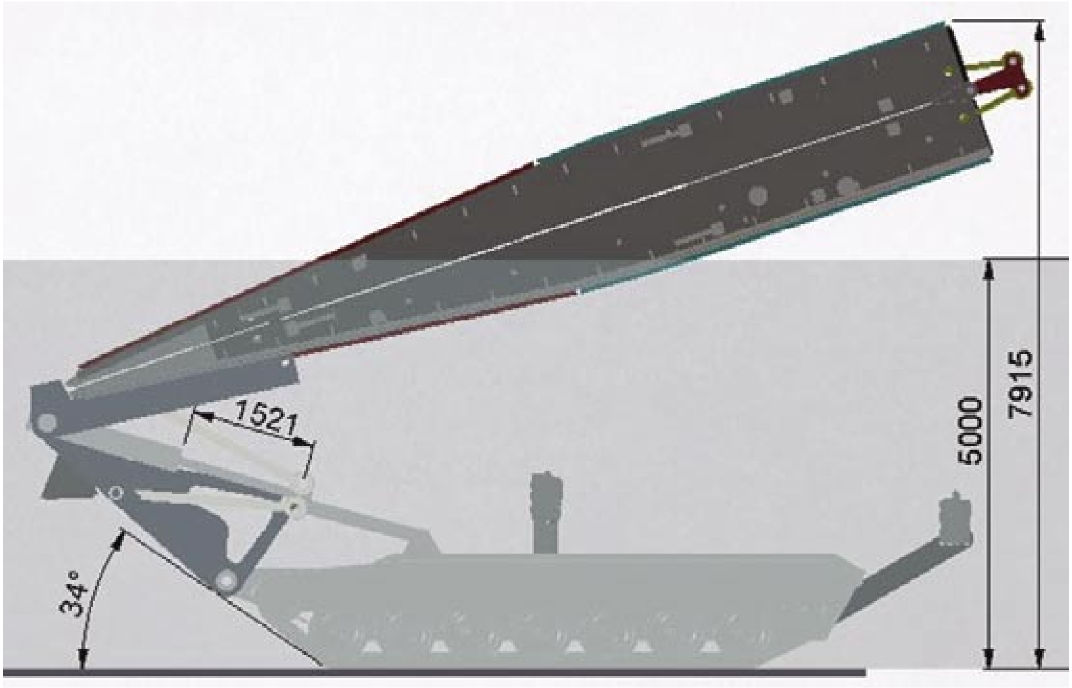

Fig. 8. Crossing with the bridge span raised

When the bridge span reaches above the water level so that the centre of gravity of the span is above the water surface:

- the displacement force is reduced by the weight of water displaced by the part of the span positioned above water (estimated at ca. 150 kN, the apparent weight of the vehicle above water is increased by this value – pressure exerted on the bottom). The exact values depend on the angle of span indination;
- the side thrust will decrease by about 30 - 40%, which will significantly improve the stability of the moving vehicle, while the side thrust line will approach the apparent weight line and the moment turning the back of the car with the river current will disappear. The fording model of the bridge will become similar to that of the tank;
- the conditions of vehicle abandonment via the driver and commander hatches improve. In the case of the span arranged in the transport position these conditions are more difficult, particularly in the case of the commander's hatch [2];
- the crossing preparation time is very similar to time of tank preparation for underwater crossing;
- the front drag is increased due to front surface area increased by 3 m^2 to 46.7 kN (at driving speed 2 m/s), which is a disadvantage. However, its effect on the required ground adhesion is compensated by the increase in apparent weight (pressure on the bottom). Thus,
  - for overcoming front drag: $\mu_{boundary} = 0.17$
  - for moving on flat bed: $\mu_{boundary} = 0.17 + 0.1 = 0.27$
  - for exiting the ford: $\mu_{boundary} = 0.17 + 0.1 + 0.3 = 0.57$

Taking into account the component of the friction force perpendicular to the direction of the crossing to compensate for the reduced side thrust leads to the boundary values of the adhesion coefficient of 0.36 - 0.42 - 0.65, respectively, thus significantly lower than the in the case of crossing with the span submerged.

The highest requirements on ground adhesion are set for the moment of exiting the ford. These requirements depend on the bank grade angle, and not on the pressure exerted by the vehicle.

An attempt to negotiate the water obstacle using this method should be preceded by additional tests of vehicle movement with the raised span to determine the method of lifting the span and of its possible blocking for the duration of the crossing.

Another issue is the maintaining of stability when exiting the ford. Raising of the span elevates the centre of gravity, wherein the displacement force of the chassis should be taken into account. Fig. 9 shows the calculated position of the centre of gravity of the vehicle with raised bridge span. To confirm stability, a check was made to see whether the line of resultant force (vehicle weight, displacement of vehicle and raised span – Q_C) crosses the outline of the track and bottom contact area.

Vehicle inclination angle: 30%

With the continuation of the movement and ascent of the vehicle chassis, the stability of the vehicle improves due to the disappearance of the chassis displacement force.

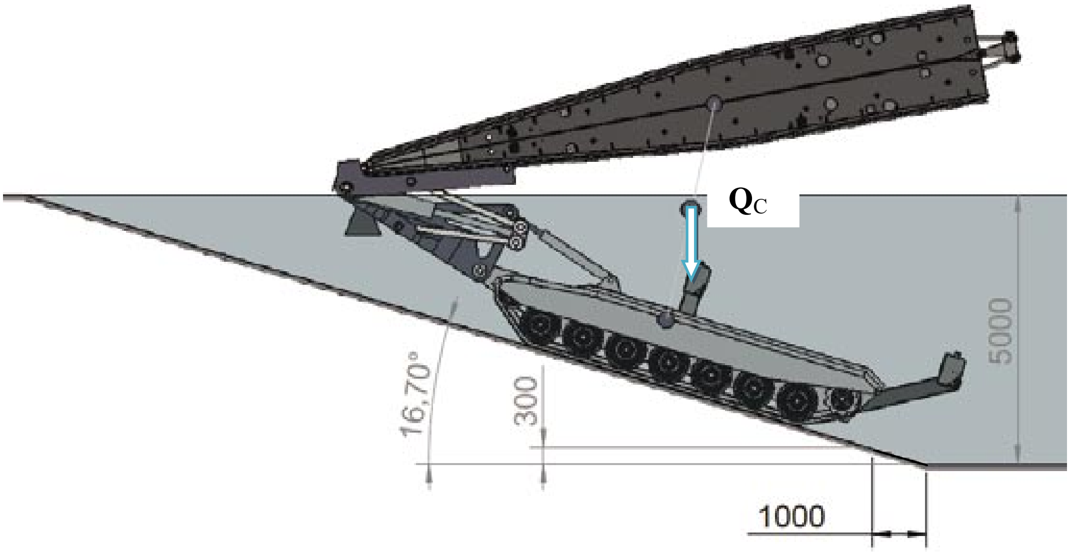

Fig. 9. Crossing with the bridge span raised (exiting the ford)

As can be seen in Fig. 9, there is a sufficient margin of stability, the Q_C force line crosses the area of track and ground contact between the fourth and fifth wheel of the vehicle.

2.5. Assessment of the ability to negotiate water obstacle with towed bridge span

A scheme of obstacle crossing with the span towed is shown in Fig. 10.

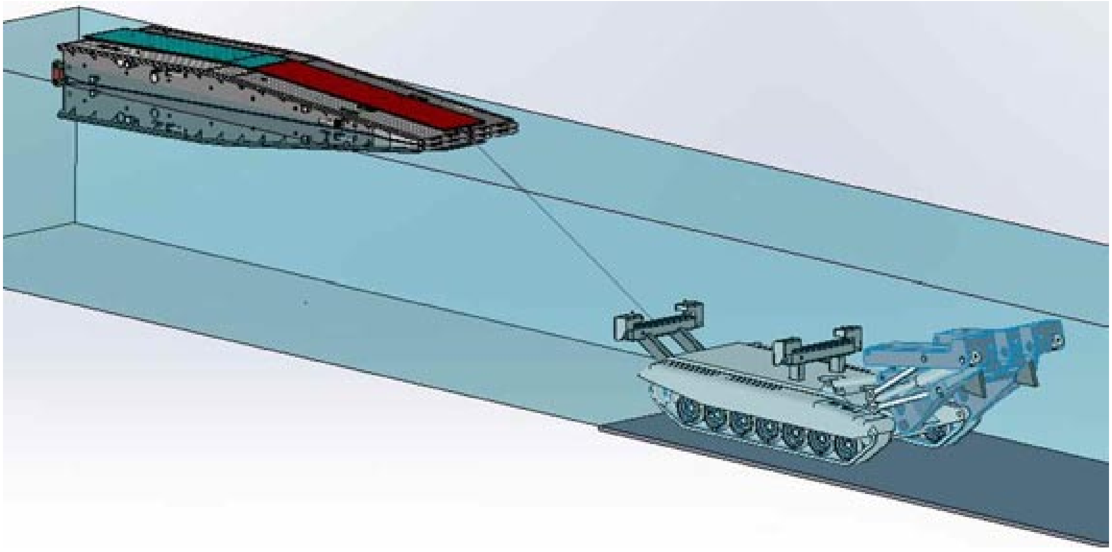

Fig. 10. Crossing with the bridge span towed

In the case of crossing standing water, the pressure of the vehicle towing on the ground does not differ significantly from the apparent weight of the chassis (the difference results from the vertical component of the pull force of the floating span) and amounts to 196 kN. Also, the total front drag does not differ significantly from that for the crossing with the span raised. As previously, the calculatuions come down to the values of the adhesion coefficient. Thus,

- for overcoming front drag: $\mu_{boundary} = 0.23$
- for moving on flat bed: $\mu_{boundary} = 0.23 + 0.1 = 0.33$
- for exiting the ford: $\mu_{boundary} = 0.23 + 0.1 + 0.3 = 0.63$

Side thrust on the chassis: 33.4 kN

Front drag (on the chassis): 19.7 kN

The component force in the rope of the towed span should be added to the side thrust: ·8,56 kN, hence the boundary side friction coefficient is: $\mu_b = 0.214$.

The side thrust increases the value of the adhesion coefficient $\mu_{boundary}$ to 0.31 – 0.39 – 0.67, respectively.

Notes:

- in terms of dynamic parameters, crossing with the span towed is one that is closest to the crossing by a tank;
- as seen from the values of the friction coefficient the situation is more favourable than the crossing with the span fully submerged and is similar to the crossing with the span raised;
- in the case of perpendicular water flow, the span is carried away by the stream and is set at a certain angle to the vehicle travel direction. That angle depends on the vehicle speed, water flow velocity, front drag of the span and side thrust of the span (limited to the part that is submerged). For the set travel speed and water flow velocity (2 m/s) the ratio of the side thrust to the front drag of the span itself is important. We may initially assume that it corresponds to the ratio of the side surface area to the front surface area. The angle between the tow rope and the travel direction will be equal to ca. 72°;
- the component force that acts to turn the back of the chassis in the direction of water flow will be equal to ca. 9 kN, resulting in the moment of rotation of ca. 46 kNm. This value is twice as high as that of the moment encountered when negotiating the obstacle in a fully submerged condition. Even if account is taken of the increased apparent weight (119 kN to 216 kN), the moment acting to turn the back of the vehicle is relatively higher by about 25%, therefore the risk during the crossing under the arrangement shown in Fig. 9 is higher. The solution to this problem would be to attach the towed span to a point in the area of the chassis centre, rather than the rear beam; in such case the moment would be zeroed;
- when the vehicle reaches the bank, the span remains in the water obstacle at a distance equal to the length of the tow rope and must be pulled up by the chassis on the ground to enable its lifting.

The conclusion can be drawn that the conditions of crossing with the span towed do not differ, in terms of dynamic parameters, significantly from the conditions of the crossing by the chassis only, and these in turn, from the conditions of crossing by armoured vehicles. However, the duration of the crossing is significantly increased, as it also includes the operation of detaching the span, fastening the tow rope, pulling the span to the other bank, unhooking the rope and lifting and attaching the span (preferably with the use of chains).

It is assumed that the span is water-tight, its displacement is higher than its weight, so it floats on water. Under combat conditions the bridge span may suffer damage and its flotability may be endangered, in which case this manner of crossing will be impossible.

2.6. Assessment of the ability to negotiate water obstacle with flooded bridge span

In this case, in order to increase the apparent weight, the span is filled with water for the duration of the crossing. The span may be filled with water fully or partially. To ensure shorter crossing time, water ports should have larger cross-sections so that filling and emptying of the span is quicker (redesign of the span required). During normal use and operation the ports should be plugged.

In dynamic terms, the conditions of obstacle crossing are as follows:

- apparent weight of the bridge increases to ca. 300 kN;
- side thrust and front drag remain the same as in the case of submerged span;
- exiting the ford (climbing) seems to be the critical stage. If water is not drained quickly from the span, the weight of the vehicle may temporarily approach 70,000 kg and the suspension of the vehicle will be exposed to overload.

The option that includes filling the span with water is feasible. However, it requires a redesign of the span to enable quick filling with water and quick draining.

3. SUMMARY

All the methods of negotiating obstacles described and assessed above are feasible under defined conditions.

Due to the dynamic parameters, the most risky is the crossing with the span submerged. Its advantage is the shortest preparation time; however, evacuation from the commander's position may be impeded.

Crossing with the span raised improves the dynamic parameters of vehicle movement across the obstacle as compared to that of the vehicle with the span resting on the vehicle. This, however, requires additional studies to work out the details of protection of the raised span against damage.

Crossing with the span towed, is flawless in dynamic terms, but the duration of crossing is significantly longer. Recovering the span may also pose problems. The girders of the span must be perfectly water-tight.

Crossing with the span flooded is also technically feasible. The preparation time is in this case longer than in the raised span method. The span would in this case require redesigning (modification of documentation) and testing, as is the case with previous methods.

The calculated required values of ground adhesion coefficients may be burdened with error resulting from the estimation of some values, e.g. of rolling resistance. However, for comparative purposes of different crossing methods, their exact values are not necessary.

For the final selection of the crossing method, an additional test program should be developed as part of the testing of the first product.

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