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# Analysis of Forces and Stability in Submerged Land Vehicle During Deep Fording Operations

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***Abstract*: An amphibious vehicle floats on the water surface and its mobility is not limited by the depth. For most submerged land vehicle (SLV), water operations are limited to fording. In this paper we will carry out an analysis on an SLV which is one of the most widely produced post-World War II and used world over by a large number of countries. This being a nascent field the behaviour of the submerged land vehicle during deep fording is still not much publicised. Hence during deep fording the dynamic forces that act on the SLV are unknown. These forces directly influence and affect the stability of the SLV under water. Therefore there is a need to analyse the flow around the SLV.***

***Index Terms*: Submerged land vehicle, deep fording, CFD, stability, dynamic forces.**

## I. INTRODUCTION

Amphibious vehicles have been in service for many years. The necessity for an amphibious vehicle arose from unprecedented demand of WW II to move large amounts of equipment and supplies from ships to storage facilities where no ports existed[1]. Though land vehicles are designed for land operations only, their operations in water are limited to medium and deep fording only at a specified speed without satisfying the floatation requirements[2]. During deep fording the SLV drives fully submerged on the riverbed/lakebed/seabed and uses a snorkel that reaches above the water surface for air supply to the crew and engine as shown in Figure 1.

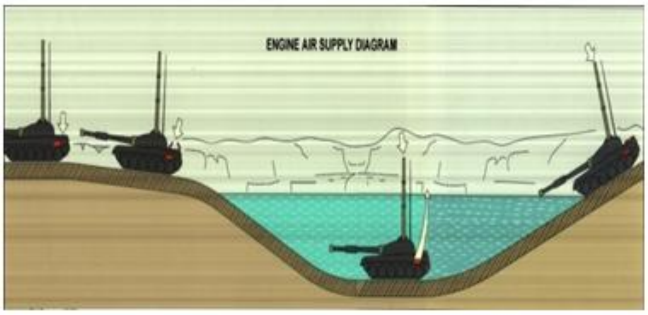


**Fig.1** SLV deep fording operation.

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The Submerged Land Vehicle should be able to ford across a water obstacle without getting bogged. The fording depth is usually limited by the height of the air intake of the engine, and to a lesser extent the driver's position. The said SLV, like all post-world war SLVs, has exemplary water crossing capabilities using the underwater stream crossing equipment .The underwater stream crossing equipment of the SLV is intended for crossing the water barriers (up to 5-m deep and 1000-m wide) with the SLV moving over the bottom. The underwater stream crossing equipment does not hinder the combat operations after crossing the water barrier without stopping the SLV and any work making the crew to go out of the SLV as shown in Figure 2.

**Fig.2** SLV emerging out after deep fording (canal crossing)

The effect of the water current becomes a key performance factor when the water obstacle is wide. Therefore the hydrodynamic analysis of the Submerged Land Vehicle to meet the mission requirement becomes an important design feature. Similar is the case of Submerged Land Vehicle carrying out deep fording through a water obstacle. In the analysis and design of such objects the knowledge of the forces exerted on them by the fluid is of significant importance[3]. If a body of arbitrary shape held immersed in a large stationary mass of fluid is moved with constant velocity through the fluid the body experiences a force which tends to oppose its motion [4]. The body in turn exerts a force on the fluid, since every action is accompanied by equal and opposite reaction. Now if a uniform velocity equal in magnitude to that of the moving body but opposite in direction is applied to the above system then the body will be held stationary and the fluid will be moving in the opposite direction.

The element of this force in the direction is said to be *drag* $F_D$ and the element perpendicular to the direction of motion is called the *lift* $F_L$, as shown in Figure 3.

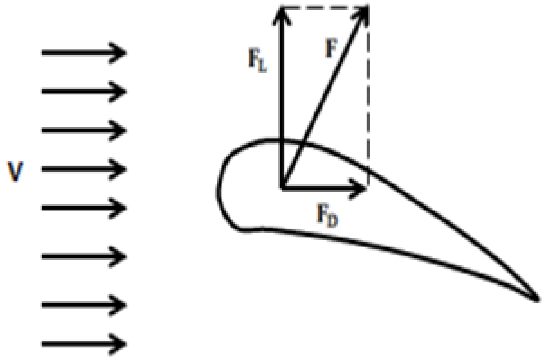


**Fig.3** Forces on an immersed body.

The force acting at any point on the small element dA of the surface of the body is judged to have some fields (tdA) and (pdA) performing beside the directions tangential and usual to the surface respectively as shown in Figure 4.

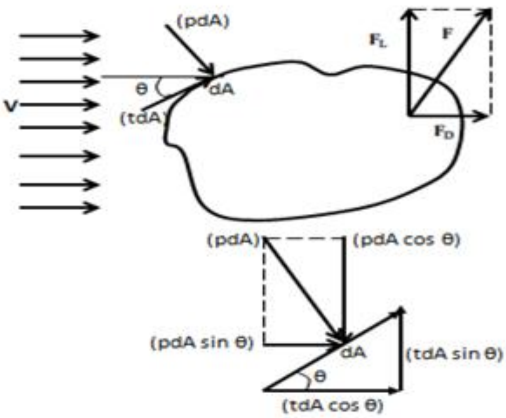


**Fig.4** Component of pressure and frictional forces on an element

The tangential components are 'shear forces' and the normal components are 'pressure forces'. The drag on the body is therefore given by the summation of the components of these forces acting over the entire surface of the body in the direction of the fluid motion. The sum of the components of the shear forces in the direction of flow of fluid is called the *friction drag* $F_{Df}$, which may be expressed as shown in Eqn (1).

*Friction drag* $F_{Df}=\int_A tdA\cos\theta$ (1)

Similary the sum of the components of the pressure forces in the direction of the fluid motion is called the *pressure drag* $F_{Dp}$, which may be expressed as as shown in Eqn (2).

*Pressure drag* $F_{Dp}=\int_A p\,dA\sin\theta$ (2)

The total drag $F_D$ acting on the body is therefore equal to the sum of the friction drag and the pressure drag as shown in Eqn (3).

$F_D = F_{Df} + F_{Dp} = \int_A tdA\cos\theta + \int_A pdA\sin\theta$ (3)

The lift on the body is given by the summation of the component of the shear and the pressure forces acting over the entire surface of the body in the direction perpendicular to the direction of the fluid motion. Thus, following expression is obtained for the total lift $F_L$ acting on the body as shown in Eqn (4).

$F_L = \int_A tdA\sin\theta + \int_A pdA\cos\theta$ (4)

For a body moving through a fluid of mass density p, at a uniform velocity V, the mathematical expressions for the calculation of the drag and the lift may also be written as shown in Eqn (5)&(6):

$$F_D = C_D A \frac{\rho V^2}{2} \quad (5)$$

$$F_L = C_L A \frac{\rho V^2}{2} \quad (6)$$

In the above expressions $C_D$ and $C_L$ are known as the drag and the lift coefficients respectively both of which are dimensionless. The area A is a characteristic area, which is usually taken as either the largest projected area of the immersed body or the projected area of the immersed body on a plane perpendicular to the direction of flow of fluid. The term ($\rho V^2/2$) is the dynamic pressure of the flowing fluid. In the case of several objects the area may be represented in terms of a characteristic length L, in which case above equations may be expressed as shown in Eqn (7)&(8).

$$F_D = C_D L^2 \frac{\rho V^2}{2} \quad (7)$$

$$F_L = C_L L^2 \frac{\rho V^2}{2} \quad (8)$$

Similarly a SLV under water also experiences a resistance force against motion when it moves forward by the motion of its tracks. The forces are lift and drag. The component of the force along the stream line is called the DRAG and the component of the force orthogonal to the stream line is called the LIFT as shown in Figure 5(a) & (b).

Such that drag force D is given as shown in Eqn (9).

$$F_D = C_D A \frac{\rho V^2}{2} \quad (9)$$

And lift force L is given as shown in Eqn (10).

$$F_L = C_L A \frac{\rho V^2}{2} \quad (10)$$

In the above expressions $C_D$ and $C_L$ are the drag and the lift coefficients respectively both of which are dimensionless.

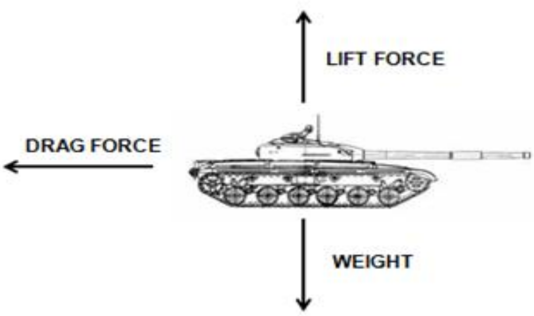


**Fig.5(a)** Forces acting on a SLV.

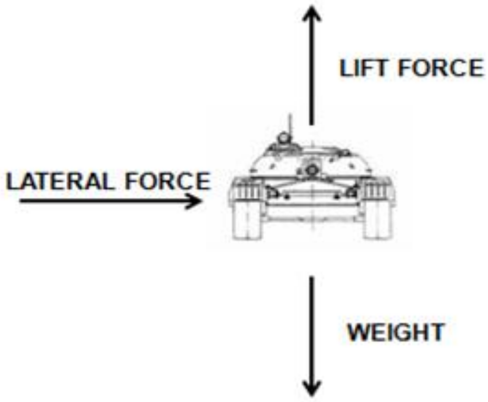


**Fig.5(b)** Forces acting on a SLV.

## II. FACTORS AFFECTING OFF-ROAD VEHICLE PERFORMANCE

In this paper we will carry out analysis on the said SLV. The major external forces acting on a SLV are as shown in Figure 6.

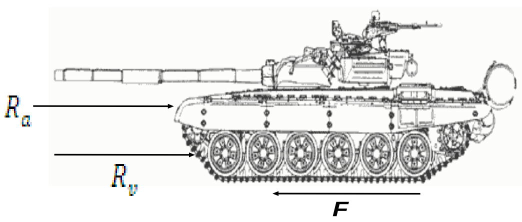


**Fig.6** External forces acting on a SLV.

In the longitudinal direction, they include the thrust (tractive effort or propelling force) $F$, fluid resistance (drag) $R_a$, the motion resistance acting on the vehicle running gear $R_v$ and resistance due to gradient $R_g$. In the present case $R_g = 0$ as we consider the water body bed as flat. Under steady-state operating conditions the equation is simplified to as shown in Eqn (11).

$$F \quad R_a + R_v \tag{11}$$

Dimensions of the SLV are assumed as shown in Figure 7.

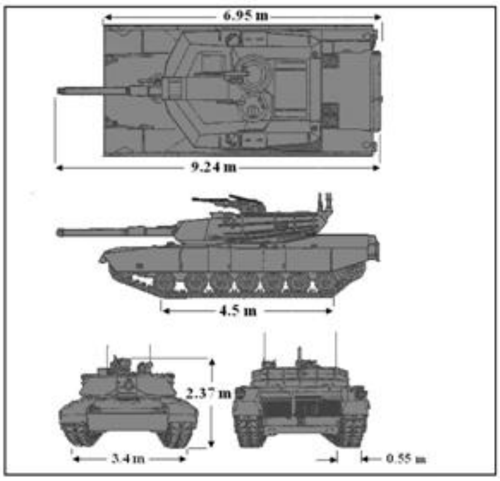


**Fig.7** Dimensions of SLV

**Table.1** Terrain Values

| Terrain | Moisture content (%) | $n$ | $k_c$ | | $k_\phi$ | | $c$ | | ø |
|---|---|---|---|---|---|---|---|---|---|
| | | | lb/in² | kN/m² | lb/in² | kN/m² | lb/in² | kPa | deg |
| Dry sand Land Locomotion Lab., LLL | 0 | 1.1 | 0.1 | 0.99 | 3.9 | 1528.43 | 0.15 | 1.04 | 28 |
| Sandy Loam | 15 | 0.7 | 2.3 | 5.27 | 16.8 | 1515.04 | 0.25 | 1.72 | 29 |
| (LLL) | 22 | 0.2 | 7 | 2.56 | 3 | 43.12 | 0.2 | 1.38 | 38 |
| Sandy Loam | 11 | 0.9 | 11 | 52.53 | 6 | 1127.97 | 0.7 | 4.83 | 20 |
| Michigam (Strong Buchele) | 23 | 0.4 | 15 | 11.42 | 27 | 808.96 | 1.4 | 9.65 | 35 |
| Sandy Loam | 26 | 0.3 | 5.3 | 2.79 | 6.8 | 141.11 | 2 | 13.79 | 22 |
| (Hanamoto) | 32 | 0.5 | 0.7 | 0.77 | 1.2 | 51.91 | 0.75 | 5.17 | 11 |
| Clayey Soil | 38 | 0.5 | 12 | 13.19 | 16 | 692.15 | 0.6 | 4.14 | 13 |
| (Thailand) | 55 | 0.7 | 7 | 16.03 | 14 | 1262.53 | 0.3 | 2.07 | 10 |
| Heavy Clay | 25 | 0.13 | 45 | 12.7 | 140 | 1555.95 | 10 | 68.95 | 34 |
| (Waterways experiment Stn.,WES) | 40 | 0.11 | 7 | 1.84 | 10 | 103.27 | 3 | 20.69 | 6 |
| Lean Clay | 22 | 0.2 | 45 | 16.43 | 120 | 1724.69 | 10 | 68.95 | 20 |
| (WES) | 32 | 0.15 | 5 | 1.52 | 10 | 119.61 | 2 | 13.79 | 11 |
| LETE sand(Wong) | | 0.79 | 32 | 102 | 42.2 | 5301 | 0.19 | 1.3 | 31.1 |
| Upland sandy loam(Wong) | 51 | 1.1 | 7.5 | 74.6 | 5.3 | 2080 | 0.48 | 3.33 | 33.7 |
| Rubicon sandy loam(wong) | 43 | 0.66 | 3.5 | 6.9 | 9.7 | 752 | 0.54 | 3.7 | 29.8 |
| North Gover clayey loam(Wong) | 46 | 0.73 | 16.3 | 41.6 | 24.5 | 2471 | 0.88 | 6.1 | 26.6 |
| Grenville loam(Wong) | 24 | 1.01 | 0.008 | 0.06 | 20.9 | 5880 | 0.45 | 3.1 | 29% |
| (Snow(U.S) | | 1.6 | 0.07 | 4.37 | 0.08 | 196.72 | 0.15 | 1.03 | 19.7 |
| (Harrison) | | 1.6 | 0.04 | 2.49 | 0.1 | 245.9 | 0.09 | 0.62 | 23.2 |

For clayey soil as shown in Table 1

$k_c = 13.19 \times 10^3$ N/m²

b = 0.8 m

$k_\phi = 692.15 \times 10^3$ N/m²

n = 0.5

Sinkage $$z_0 = \left(\frac{53.5666 \times 10^3}{\frac{13.19 \times 10^3}{0.8} + 692.15 \times 10^3}\right)^{1/0.5}$$

$$= \left(\frac{53.5666}{16 + 692.15}\right)^{1/0.5}$$

$$= \left(\frac{53.5666}{708.15}\right)^{1/0.5}$$

$$= 0.0756^{1/0.5}$$

∴ Sinkage $z_0 = 0.0057$ m

Compaction resistance $$R_c = 2b\left(\frac{k_c}{b} + k_\phi\right)\frac{z_0^{n+1}}{n+1} \tag{15}$$

$$= 2 \times 0.8 \left(\frac{13.19 \times 10^3}{0.8} + 692.15 \times 10^3\right)\frac{0.0057^{1.5}}{1.5}$$

$$= 1.6\,(708 \times 10^3)\frac{0.0057^{1.5}}{1.5}$$

$$= 1.0666 \times (708 \times 10^3) \times 0.0057^{1.5}$$

$R_c = 327.0523$ N

## III. THRUST (TRACTIVE EFFORT OR PROPELLING FORCE)

The thrust $F$ as verified by the attributes of the power plant and transmission is articulated as shown in Eqn (16).

$$F = \frac{M_e \, \xi \, \eta_t}{r} \tag{16}$$

Where $M_e$ is the engine torque, $\xi$ is the overall gear reduction ratio of the transmission.

$M_e$ = 3089 Nm
$\xi$ = 8.1714 in first gear
r = 0.265 m
$\eta_t$ = 88%

$$F = \frac{3089 \times 8.1714 \times 0.88}{0.265} = 83.818 \text{ kN}$$

The obstacle resistance $R_{ob}$ and the internal resistance of the running gear $R_{in}$ have to be determined experimentally. The resistance offered by an equipment casualty to movement during its extrication is a combined effect of the following three types of resistances:-

### 3.1 Rolling resistance

The rolling resistance offered by an equipment casualty is dependent upon:-

(a) The resistance to movement inherent in the casualty itself, due to its weight.

(b) The nature of ground and soil over which the casualty is to be moved. The rolling resistance offered varies with the type of ground surface and the soil. The approximate rolling resistance offered by an undamaged vehicle on various type of ground expressed as a fraction of its weight W is as shown in Table 2.

**Table.2** Rolling Resistance in terms of weight

| Type of ground | | weight fraction |
|---|---|---|
| (a) | Smooth road | W/25 |
| (b) | Grass | W/7 |
| (c) | Gravel | W/5 |
| (d) | Shingle beach | W/3 |
| (e) | Sand hard and wet | W/6 |
| (f) | Sand Soft andwet | W/5 |
| (g) | Sand loose and dry | W/4 |
| (h) | Black mud | W/2 |
| (j) | Soft blue clay | W/2 |

### 3.2 Gradient Resistance

The effort required to move a load up a slope is always more than that required to move the same load along a level surface. Further, as the gradient increases, there is a corresponding increase in the effort applied. This increase in effort is necessary to overcome the resistance offered because of the slope and is known as the gradient resistance. For slopes upto 45 degrees, the gradient resistance offered by a casualty of weight W may be taken as W/60 per each degree rise in the gradient. For slopes more than 45 degrees, if encountered, the gradient resistance should be taken equal to the weight W of the casualty.

### 3.3 Damage Resistance

Damaged equipment offers additional resistance to motion which will depend upon the extent and nature of damage and the parts damaged. The damage resistance will therefore vary for each casualty and can be assessed only by judgment based on past experience. In case of SLVs whose tracks get locked, it has been found that resistance offered in terms of their weight W is as much as:-

(a) W/2 - when one track is locked.

(b) W - when both tracks are locked.

However in this paper we consider the SLV to be undamaged and hence damage resistance as zero.

## IV. CALCULATION OF LOAD

If a casualty offers a rolling resistance R, a gradient resistance G and a damage resistance D, then the total resistance T offered by it is given as shown in Eqn (17):-

$$T = R + G + D \qquad (17)$$

### 4.1 Estimated Pull.

The total resistance must be increased by a factor of safety to allow for any inaccuracies in estimating and for any unforeseen resistances in the equipment or in the extrication of the casualty as also certain random small variables not taken into account. The factor of safety used is 25 percent or a quarter of the total resistance. The Estimated Pull (EP) will therefore, be equal to 5/4 T. Since the rolling resistance offered varies with the type of ground surface and the soil, considering the approximate rolling resistance offered by an undamaged vehicle on Sand loose and dry expressed as a fraction of its weight W as W/4 and factor of safety as 1.25 the motion resistance acting on the vehicle running gear $R_v$ is

$$R_v = \frac{5}{4} \times T$$

$$= \frac{5}{4} \times \frac{W}{4}$$

$$= \frac{41.5 \times 10^3 \times 1.25}{4}$$

$R_v$ = 12.9687kN

Thus the equation can be simplified to as shown in Eqn (18).

$$F = R_z + 12.9687 \text{ kN} \qquad (18)$$

## V. DYNAMIC STABILITY

The SLV can be considered to be dynamically stable during deep fording if

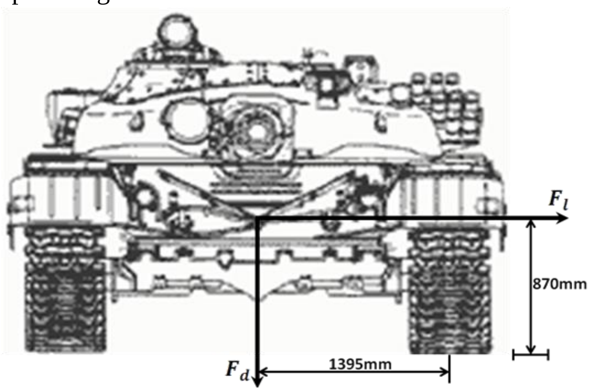


**Fig.8** Rolling forces acting on a tracked vehicle

(a) The value of $F$ (thrust) is greater than the value of ($R_z$ + 12.9687 kN) in the 'X' plane

(b) The value of W is greater than the sum of buoyant force and lift force in the 'Y' plane

(c) The rolling force caused due to the lateral force in the 'Z' plane is less than the turning moment caused due to W as shown in Figure 8.

Force acting in Y plane = $F_d$ = Weight of the SLV – (Buoyant Force + Lift Force)

Buoyant Force= volume of the SLV x density of water x 9.81

∴Buoyant Force= volume of the SLV x $10^3$ x 9.81

Lateral force = $F_l$

Rolling of the SLV is possible if the turning moment due to force acting in downward direction is less than the turning moment caused due to the lateral forces

ie $F_d$ X 1.395 < $F_l$ x 0.87

For analysing the stability of the SLV we can consider the cases when the SLV motion is perpendicular, opposite and in the direction of flow and the corresponding $R_a$ will determine the dynamic stability of the SLV. However it is not possible to calculate the values of Drag Force $R_a$, Lift force and Lateral force $F_l$ by analytical methods. The same can be calculated using Computational Fluid Dynamics (CFD). Below figure represents the framework used here to evaluate the dynamic stability of the SLV based on the force description presented in above sections.

The future research will focus on developing the required CFD model so that the values of Drag Force $R_a$, Lift force and Lateral force can be calculated as shown in Figure 9.

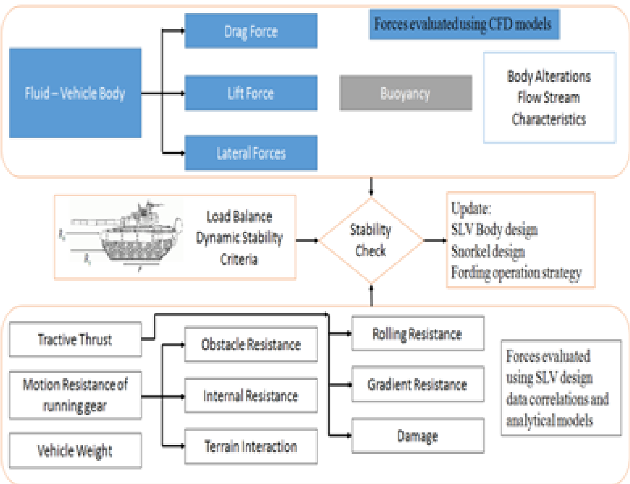


**Fig.9 Force analysis for dynamic stability of SLV during deep fording operation**

## VI. CONCLUSION

In this novel work an existing SLV design has been examined in terms of deep fording capabilities. This paper proposes a method for the analysis of the various forces involved during the deep fording operation of an SLV under water and the factors affecting the dynamic stability of the SLV during its motion. The detailed simulation analysis can be carried out by using CFD to determine the values of various forces acting on the SLV for further calculations. These data will help in taking field decisions. The simulation carried out will provide adequate insight about the deep fording capability of the vehicle.

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