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Drag and lift contribution to the incipient motion of partly submerged flooded vehicles

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ABSTRACT

At present, the vehicles instability during an urban flood is recognized as being one of the most exacerbating factors for flood risk, particularly for people's safety. In this work, the incipient motion conditions of flooded vehicles are investigated and discussed. A mobility parameter θ_V is here introduced as a function of the Froude number of the flow. A 3-dimensional numerical model describing the flow for different regimes past a specific vehicle geometry is presented to clarify the contribution of drag and lift forces to the incipient motion conditions. The results highlight the strong influence of the Froude number on the forces with a different dependence on it of drag and lift coefficients. The numerical results are compared with recent experimental data found in literature on partially submerged vehicles. The comparison confirms the crucial role of the friction coefficient and reveals the uncertainties introduced by the assumption of the car as a rigid body. The estimated force coefficients may provide a useful tool for flood risk assessment and management in urban areas.

1. Introduction

The constant increase of the population living in the cities (UN Department of Economic and Social Affairs, 2010) and the concerns related to the climate change (Milly et al., 2002) make flood risk in urban areas a crucial issue in terms of potential damages, casualties and injuries to the people (WMO, 2008). Vehicles are usually recognized as being one of the most aggravating factors in case of flood in the urban environment (Rodriguez et al., 2006). In fact, vehicles can become unstable by losing traction or can become buoyant so that they are mobilized by floodwaters and possibly produce a debris. The main consequences of such a debris are a reduction in the safety of the people, additional damages to buildings and infrastructures, and potential blocking of the hydraulic structures (e.g. bridges). Therefore whereas on one hand the vehicles play an active role in aggravating the local flood parameters (dangerous floating debris, flood depth, velocity), on the other hand they are indirectly responsible for many people's fatalities.

In the last decade many studies (Jonkman and Kelman, 2005; Maples and Tiefenbacher, 2009; Fitzgerald et al., 2010; Kellar and Schmidlin, 2012) have shown that the first cause of death in a city during a flood event is related to the roads. Jonkman and Kelman (2005) reported that in the Netherlands the 33% of deaths for drowning during a flood occurs in a vehicle and the 25% as a pedestrian. Maples and Tiefenbacher (2009) show that a minimum of 216 deaths were caused by

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automobile immersion on flooded roadways in Texas during the study period 1950–2004 and a positive trend is found. Fitzgerald et al. (2010) argue that the 48.5% fatalities are related to motor vehicle use and 26.5% fatalities occurred as a result of inappropriate or high-risk behaviour during floods (included driving in flooded streets).

Although the vehicles are so critical during floods in urban areas, a limited number of studies have been carried out on the behaviour of cars facing a flood flow. A distinction should be made on the purpose of these studies. While for road safety purposes the conditions of moving vehicles on a wet surface are considered (e.g. the road–tyre adherence), for urban flood safety also a parked car is considerable. A common flooding situation is the one caused by failure of the street drainage system for intense rainfall, with flood depth up to 0.2 m and velocities up to 0.5 m/s. Much less studied is the vehicle interaction with flow conditions typical of river inundations or flash floods. Most of the existing works have been done for road safety purposes as flume experiments in 1960s and early 1970s (Bonham and Hattersley, 1967; Gordon and Stone, 1973) and as theoretical analysis in the early 1990s (Keller and Mitsch, 1993). However, substantial changes in vehicle design have been introduced since these early studies, especially in vehicle planform area, vehicle weight and ground clearance and the results of these earlier studies may no longer be representative of contemporary vehicles (Shand et al., 2011).

The two recognized hydrodynamic mechanisms by which the stability of a stationary vehicle is lost are floating and sliding. Assuming that a car cannot be filled quickly by floodwater, its density is much smaller than water density and most of the weight is usually distributed in the lower front part (close to the engine in the majority of modern cars). The floating instability occurs when the buoyancy and lift effect exceed the weight of the car. The sliding instability occurs when the drag force exceeds the resistance force (i.e. tyre/road friction). These two mechanisms interact as the effect of buoyancy and lift reduce the normal component of the weight thus promoting sliding conditions even for very low water depths.

Recently, some experimental studies have been carried out to investigate, at the laboratory scale, the behaviour of the vehicles at rest in flooded streets (Shu et al., 2011; Xia et al., 2011).

In the study by Xia et al. (2011), starting from the balance of the forces acting on the vehicle, a formula has been derived to predict the incipient velocity of flooded vehicles according to the mechanical condition of sliding equilibrium. A series of flume experiments were conducted using three types of scaled die-cast model vehicles, with two scales being tested for each type of vehicle (1:43, 1:18). The vehicle scale model was filled by floodwater so their density was larger than water density.

In the study by Shu et al. (2011) the experiments on the incipient motion due to sliding mechanism have been carried out using different waterproof scale models (1:18) in partially submerged conditions. The experimental results were used to assess the incipient motion velocity for prototype cars, based on scale ratios.

Since the studies on the incipient motion are usually carried out through laboratory experiments, as the above mentioned, this work aims at the assessment of the different contributions to incipient motion given by hydrodynamic forces through a numerical model. The numerical approach to the problem of incipient motion of vehicles glances at the study of free surface flows past bluff bodies. The flow around a fully submerged rectangular cylinder and other simple-shape bodies has been studied by many researchers so far both numerically (Lam et al., 2012) and experimentally (Malavasi and Guadagnini, 2007).

There are only a few references for partially-submerged conditions and subcritical flow conditions (Malavasi and Guadagnini, 2003; Arslan et al., 2013) and no references for partially submerged complex objects leaning on a channel bed under both subcritical and supercritical flows. Transition to supercritical conditions may substantially alter the pressure distributions and the resulting drag and lift forces, as already observed in the study of hydrodynamics of marine vehicles (Chapman, 1972; Savitsky and Ward Brown, 1976; Faltinsen, 2006).

First, the aim of this work is to describe the incipient motion conditions of flooded vehicles observed in the above flume experiments, in order to identify the relevant dimensionless parameters and scaling numbers. The second aim is to assess numerically the contribution of drag and lift forces acting on a partially submerged vehicle when incipient motion occurs, using a 3D numerical model, and relate them to the scaling parameters. Notably the focus is to understand on one hand the dependencies of hydrodynamic forces on flow characteristics and on the other hand to assess the relevance of drag and lift contribution in the global balance of forces. In fact, given the large variability of available experimental data, flow conditions and given the uncertainties on vehicle specific geometry and flow orientation, it will not be required to evaluate the value of force coefficients with an accuracy larger than the accuracy of the available experiments, but the overall flow–vehicle interaction.

In Section 2 of this paper the incipient motion conditions of partially and fully submerged vehicle are analysed. The experimental data (Xia et al., 2011; Shu et al., 2011) are used to verify the adimensional groups adopted to describe the threshold of incipient motion. The experimental data on the incipient motion of the Ford Focus scale model by Shu et al. (2011) are also reproduced and extended to prototype model, with a 3D numerical model set in OpenFOAM (Section 3) using a detailed geometry of the car. The results of the dimensional analysis and of the numerical simulations are shown and discussed respectively in Sections 2 and 4.

2. Incipient motion conditions from Xia and Shu flume experiments

2.1. The mobility parameter θ_V

The incipient motion of flooded vehicles can be approached with some similarity to the study of sediment transport in rivers, also taking into account the peculiar features of the vehicles. The main differences between a sediment particle and a vehicle, which influence the incipient motion are specific weight, weight distribution, position over the channel bed, and submergence.