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FLOW AND DISPERSION MODELLING IN A COMPLEX URBAN DISTRICT TAKING ACCOUNT OF THE UNDERGROUND ROADS CONNECTIONS

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Abstract: In the study of accidental or intentional releases of hazardous materials, dispersion modelling based on computational methods is increasingly used. The spatial resolution which can be reached is about one to a few meters with a system like PMSS, Parallel-Micro-SWIFT-SPRAY. At the local scale, explicitly taking account of the flow and dispersion of pollutants within the underground roadways and the tunnels may be very important. As a matter of fact, modern districts like "La Defense" (in the Western part of Paris) have so complex road connections that it may be influential on the propagation of plumes.
A new feature in PMSS dealing with underground tunnels have been implemented, tested and applied on the "La Defense" area.

Key words: *underground roadway, tunnel, PSWIFT, PSPRAY, urban environment*

INTRODUCTION

PMSS, Parallel-Micro-SWIFT-SPRAY (Oldrini et al., 2011), is a fast transport and dispersion modelling system. It is designed for local scale and takes buildings into account. The parallel version can be run on multi-core computers or large parallel clusters. PMSS consists of PSWIFT and PSPRAY used in urban mode (Micro SWIFT, Micro Spray).

SWIFT / Micro-SWIFT (Tinarelli et al., 2007) is an analytically modified mass consistent interpolator over complex terrain. Given topography, meteorological data and buildings, a mass consistent 3D wind field is generated. It is also able to derive diagnostic turbulence parameters to be used by SPRAY / Micro-SPRAY. Micro-SPRAY (Tinarelli et al., 2013)is a LPDM (Lagrangian Particle Dispersion Model) able to take the presence of obstacles into account. It derives from the SPRAY code and is based on a 3D form of the Langevin equation for the random velocity.

In urban applications, the spatial resolution is usually between 1 to 5 meters. The buildings that are taken into account are typically defined through geographic information system (GIS) databases such as BD TOPO® from IGN in France where each building, or block of buildings, is described by its footprint and a vertical extrusion height from the ground level. In the framework of what is often referred as "geo-design" which is a digital description of urban environment, setting together the features of both computer-aided design (CAD) and GIS, this footprint and extrusion type of description is called Level of Detail (LoD) 1. More realistic, the LoD 2, 3 and 4 include more information such as roof shape, windows locations and dimensions or even indoor description.

The LoD 1 digital models are widely available, making the setup of geometry for urban dispersion modelling at small scale quite easy. But with a spatial resolution of 1 - 5 m, the buildings are not the only geometrical objects that can be explicitly described and have a significant influence on the dispersion. The underground road tunnels are quite widespread in cities (for example, in Paris, "La Defense" area, tunnel under the forecourt of "Gare de Lyon" rail station, tunnels along the Seine river banks). However, they are quite seldom considered in urban numerical dispersion modelling. For air quality studies near tunnel portals, CFD calculations are performed, but they are limited to the evaluation of the pollutant transfer from the tunnel to the outdoor. Then, the inside of the tunnel is not explicitly modelled.

We propose here a new feature of PMSS that allows the underground tunnels and the transfer of material from tunnel to outdoor and from outdoor to tunnel to be taken into account. In the framework of accidental or malicious release in urban area, for emission near tunnel portal, this new capability could lead to more realistic prediction of material transport and thus of danger zones.

A brief description of tunnel modelling state of the art, the technical description of the implementation into PMSS and an application on “La Defense” area are presented in the next sections.

UNDERGROUND TUNNEL MODELING

Underground road tunnel

The present study is focused on underground tunnels and road connections that have a spatial scale that is compatible with the spatial resolutions typically used in PMSS (1 to 5 meters).

Besides its geometry and its mono- or bi-directional property, such tunnels are characterized by their ventilation system. The basic one is the natural ventilation. In this case, air movement relies on piston effects from vehicles motion, temperature and pressure differences at portals and outdoor wind velocity and direction. The phenomenon can also be increased by the addition of vertical shafts taking benefits of chimney effects. Natural ventilation is mainly applied to short tunnel (a few hundred of meters).

Mechanical ventilation systems can be split into two categories: the longitudinal systems and the transversal systems. In the first type, a longitudinal flow is generated by a limited number of fans at the ceiling (“jet fans”) or horizontal air injection near portal (*Saccardo* system). In the second type, a uniform supply and extraction of air is used along the tunnel length. This requires two related duct networks. If only extraction or supply is used, the system is called semi-transversal.

Modelling techniques

Dispersion in tunnel modelling is commonly used for fire safety design. Examples of 1D models are MFIRE (U.S. Bureau of Mines), SES (U.S. Department of Transportation), ROADTUN (UK), SPRINT (Switzerland), Express’Air (SETEC) or New Vendis (INERIS) . They allow a complete and compact description of complex networks (main tunnels and ventilation ducts) but with the approximation of homogeneity in cross sections. Coupling between this kind of model and outdoor dispersion models does not seem to be proposed yet.

CFD models are also applied as engineering tools for tunnel fire safety (Collela, 2010). Their computational cost limits their use to simple networks or parts of tunnel. Momentum effect of jet fans or thermal effect of fire for example can be modelled using this approach.

Hybrid methods, coupling 1D and CFD models have also been developed more recently (Collela, 2010) but they are still focused on the inside of the networks.

Material transfers from the inside to the outside of tunnel portal are also computed with CFD models (Lacour et al. 2004) for air quality purposes. Here, only the tunnel part that is close to the portal needs to be included in the calculation domain.

At larger scale, for traffic pollution study, the pollution near tunnel portal can be computed by moving the mass rate, emitted inside tunnel, to additional releases located in front of the portal.

In all these existing methods, the focus is clearly not set on the two-way material transfer. The approach described in this paper proposes a solution to fill this gap with an operational objective.

Description formats

As mentioned in the introduction, urban numerical databases are available for many cities in standard GIS formats such as shape file (ESRI). It makes the operational / automatic setup of micro-scale urban modelling possible. For urban objects, such as underground road tunnels, the availability and the format standardisation are much less mature.

In urban digital modelling new formats, based on a hierarchical structure, named LoD, are rising: CityGML or LandXML are the main ones.

In the CityGML framework, Bormann et al. (2014) have recently proposed a structure dedicated to underground tunnels where LoD1 is limited to simple polylines for mapping and where LoD5 can include the description of traffic lights or walkway, to give an example.
Some dataset samples are available (http://www.citygml.org/?id=1539) and can be visualized thanks to a tool developed by the Karlsruhe Institute of Technology. In some of them, a specific layer is devoted to underground tunnels. It is interesting also to note the holes in the topography layer, corresponding to the portals of the tunnels. Such interfaces between ground and tunnel do not exist in standard Digital Elevation Model like SRTM (CGIAR) or BDALTI® (IGN).
The detailed definition structure of underground tunnel for urban modelling is available inside the CityGML format, but the databases are not available. In the implementation proposed here, the tunnels geometry is designed in a similar fashion as building using footprints and vertical dimensions saved in the shape file format. More details are given in next section.

PMSS UPGRADE

Dealing with underground volume

To include underground tunnels into PMSS, several methods have been considered. Knowing that the nesting and tiling capabilities of PMSS rely on the use of spatial sub-domains management, the underground sections can be seen as additional and independent nest or tile structures. The other considered method consists in extending the vertical grid to negative heights from ground surface. This second method has been selected, mainly to avoid complex interface management at tunnels portals between separated sub-domains that would have been required in the first method.

PMSS grids are structured, regular in horizontal and based on a terrain following transformation for the vertical dimension (see equation (1), where H is the top of the domain, z the current altitude, z_g the ground surface altitude) as illustrated on Figure 1 (left). The vertical grid has been extended to negative value of z*, using the same transformation as for positive value (Figure 1 (right)). In the future, a dedicated transformation for negative value could be implemented because the underground volume should not be terrain-following.

$$z^* = H \frac{z - z_g}{H - z_g} \qquad (1)$$

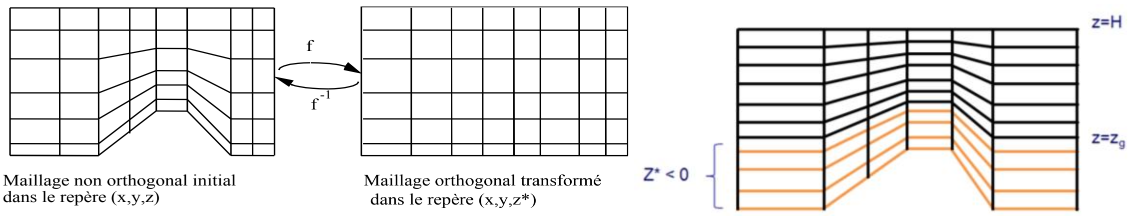

Figure 1. Left: Terrain following transformation of PMSS vertical grid –
Right : Extension of the vertical grid to negative value of z*

PMSS has been updated to be able to distinguish the first level of the vertical grid and the ground surface which are not the same anymore. PSWIFT has also been modified to set specific velocity profile in the underground tunnels (Poiseuille law for the moment as it is used for aerial tunnels in PMSS).

Input files and pre-processing

In order to have a friendly-user definition of tunnels geometry and to be consistent with the others obstacle types that can be set as input to PMSS, a LoD1 type solution based on shape file format has been implemented. The obstacles pre-processor, named Shaft, have been generalized and can load different layers in this GIS format, before extracting and translating them into the native format of PMSS. Buildings, canyon zones and now underground tunnels can be handled. In the future, others types like trees could be added. The tunnels geometry is defined by their footprint (polygon) and two attributes for each polygon corresponding to bottom and top limit height from ground surface (negative values).

Test cases

Different test cases have been set up before applying the new feature to a realistic case. Figure 2 shows one of these tests. It consists in a tunnel limited to the entering portal. The axis of the tunnel is aligned with the direction of the wind. The academic wind profile is stationary and a punctual release of tracer has been placed in the portal zone, at an altitude close to 0 meter. The results are satisfying: the flow field has a logarithmic shape above ground, a Poiseuille shape in the tunnel and a transition at the portal. The plume is split with one part above ground and one part confined into the tunnel.

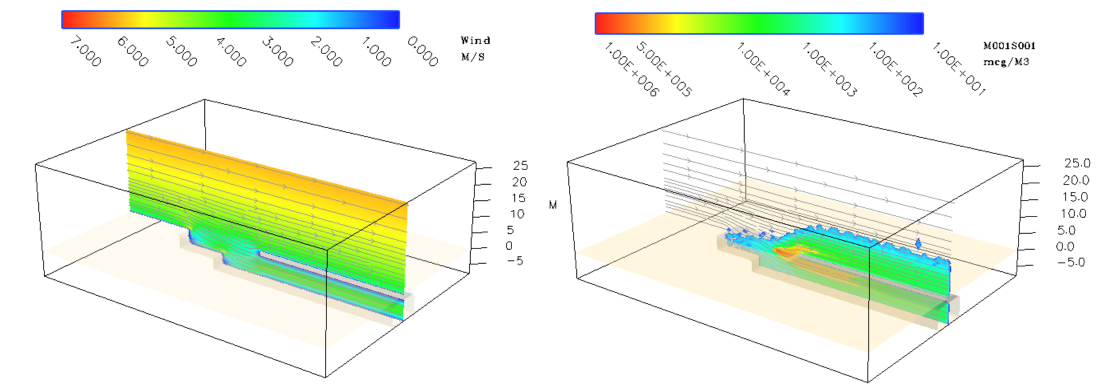

Figure 2. Simple underground tunnel test case – 3D interface surface between solid and fluid is displayed with transparency. On a vertical slice along the wind direction: Velocity magnitude and streamlines (left), concentrations and streamlines (right)

APPLICATION CASE

“La Defense” area is a complex urban domain. It is well known for its skyscrapers but also for its numerous tunnels. The BD TOPO® (IGN) has been used to define the buildings. This database has been modified to take into account aerial tunnels that are shown in orange on Figure 3 (left). The underground tunnels layer has been created from maps data and observations. The underground road tunnels considered in the calculation are displayed on Figure 3 (right).

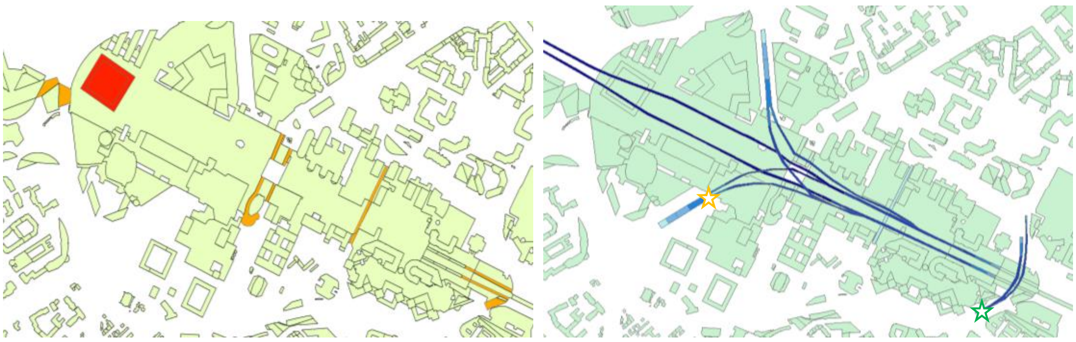

Figure 3. Left: Buildings footprints from BD TOPO® (IGN) in green and applied modifications to take into account arch structure (red) and aerial tunnels (orange). Right: Underground road tunnels in blue – Blue scale in giving the deepness of the tunnels floor – Orange and green stars show the location of considered hypothetical releases

The meteorology is driven by the extraction of 4 vertical profiles from a meso-scale model, following the operational configuration where a downscaling form WRF model to PMSS model is performed. The wind is here blowing mainly from the West. Two hypothetical releases have been considered (see Figure 3 for their locations). They are both punctual continuous releases with duration of 1 minute and a total emitted mass of 5 kg. The results are illustrated on figure 4. For both releases, the main part of material is transported and diffused above the ground but a significant amount is also confined into the closest tunnel. These amounts are then advected through the tunnels to the exit portals and back to the outdoor domain with a significant time delay.

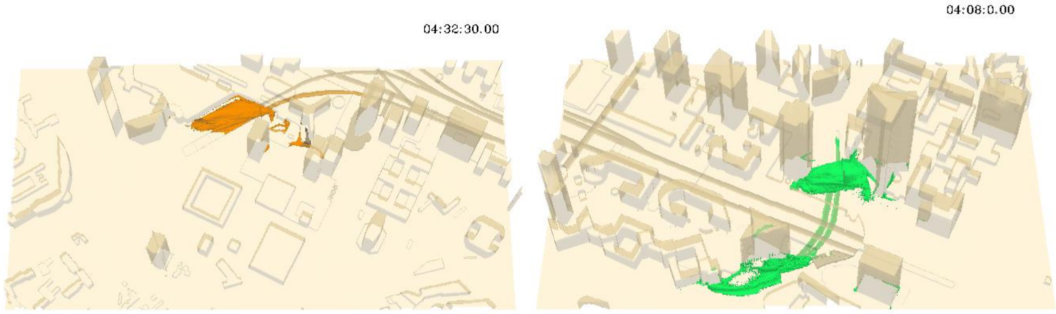

Figure 4. Left: South-West part of the calculation domain – Buildings and underground tunnels with opacity – Plume from orange release, time is 2'30'' after the beginning of the emission – 3D iso-surface at 10 mg/m3 in orange - Right: South-East part of the calculation domain – Buildings and underground tunnels with transparency – Plume from green release, time is 8'00'' after the beginning of the emission – 3D isosurface at 2 mg/m3 in green

CONCLUSIONS

While the underground tunnel databases are not available, the CityGML format has been recently used to develop the numerical description of these tunnels. PMSS model is not able to use this format yet but it will surely have to in the future. In the meantime and keeping an operational objective, the underground tunnels have been added in the panel of the objects that PMSS can explicitly model using a simple footprint and vertical extrusion definition. This first implementation has been applied on a complex domain such as "La Defense", and gives satisfying results and improves the realism of concentration field.

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