Optimization of Sunken Road Planning with Environmental Impact Analysis by CFD Simulation

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ABSTRACT

In the recent years the problem of exhaust pollution and noise caused by urban ground traffic is very serious. Numerous practices prove that the underground traffic planning is a potential solution to this problem. This paper optimizes the planning and designing of a sunken road in China by combining fundamental theory of underground space planning with up-to-date computational fluid dynamics (CFD) technology. The results of this study show that the sunken road plan has been substantially improved by adopting CFD. The results of CFD modeling provide a basis for quantitively evaluating the environmental benefits of sunken road plan and useful lessons for many similar underground projects.

1. INTRODUCTION

With the rapid economic growth and hastened urbanization progress in China, the issue of environmental pollution has caused wide public concern. In the recent years the problem of exhaust pollution and noise caused by urban ground traffic is very serious. To develop the underground traffic combined with the characteristics and advantages of underground space is an important solution to the above problem. With the development of underground traffic, it can not only improve the urban environment, protect the natural and cultural landscape, preserve the historical scene, but also decrease the influence of ground road and overhead road on local residents.

Since the effective underground traffic planning plays an active part in improving the urban ground environment, it is a valuable research subject to quantitively evaluate the environmental benefit of various tentative plans in the planning and designing stage of a construction project and then guide optimal design of the project considering the environmental benefit. As a practice of combining fundamental theory of underground space planning with up-to-date technology, this paper presents the sunken road plan for Shaoxing Road in Qingdao city and predicts the exhaust pollution of this road for different plans by three-dimensional computational fluid dynamics (CFD) modeling. With the predictions from CFD, this paper achieves a favorable plan by comparing and evaluating of different tentative plans.

2. OVERVIEW OF PROJECT

2.1 Analysis of Current Situation

The total area of the planning district is 2.1 square kilometers. The topographic feature is high in the northeast and low in the northwest and the maximum height difference for this area is about 50 meters. The resident population is 35,000. The traffic is convenient enough as the base of this region is close
to the main roads of the city. However, according to a lot of investigations, we have found that the development of this district is limited because it lacks the uniform planning, exploitation, and government regulation. In addition, since the economy of this district is dominated by traditional industry, the labor-intensive industries occupy a considerable portion and the issue of environmental pollution is serious.

2.2 Overall conception

Considering the function orientation, development strength, and supporting facilities of ground area in core district, the underground space planning of this district takes the functions of underground traffic, commerce, culture, entertainment and leisure, and disaster defense as main principles and focuses on solving the problem of commercial and cultural supporting facilities of the central business district (CBD). A highly developed underground pedestrian mall system and a round-the-clock business space will be constructed with the combination of business streets and subway stations. In each main functional area, the different functions of both ground and underground will be coordination with each other by developing underground space. As a result, the aim of improving the overall function of the city could be achieved.

![Fig. 1. Profile of the crossing between Shaoxing Road and Dunhua Road.](image)

The crossing between Shaoxing Road and Dunhua Road is a commanding point in the city. It forms a landmark of the city but produce unfavorable effects on traffic due to the tremendous changes in the road altitude. Therefore, we will lower the altitude of this node and construct the special underground space to meet the heavy demands for business supporting facilities in the residential district as well as to facilitate the separation of pedestrian and vehicular traffic. After lowering the altitude of this node, we will excavate the both sides of the road to construct the supporting business and parking facilities. Furthermore, we will pave an overpass for pedestrians at the previous altitude of the road. At last, a three-dimensional traffic will be completed as shown in Fig. 1.

3. CFD SIMULATION TOOL

With the tremendous development of the capacity and speed of personal computers, the combination of CFD and expert experience is playing an important role in the area of building planning and design. The principles of the CFD approach can be found in many textbooks, such as Patankar (1980). CFD solves the governing conservation equations of mass, momentum, energy, and air pollutant in the following general form:

$$\frac{\partial}{\partial t} (\rho \phi) + \text{div}(\rho \mathbf{u} \phi - \Gamma \phi \text{grad} \phi) = S_\phi$$

(1)

where $\phi$ is $V_j$ that stands for each of the three velocity components $u$, $v$, $w$, is 1 for mass...
continuity, is $T$ for temperature, is $C$ for different gas type of air pollutant, is $k$ for kinetic energy of turbulence, is $\varepsilon$ for dissipation rate of the kinetic energy of turbulence, and is $h$ for air enthalpy. $\Gamma_\phi$ is the effective exchange coefficient for the dependent variable $\phi$. $S_\phi$ is the source term of the general equation. More details of $S_\phi$ and the turbulence parameters of $k-\varepsilon$ turbulence model can be found in Launder and Spalding (1974).

Equation (1) can be solved by approximating turbulence quantities using a turbulence model. This study has used a $k-\varepsilon$ model (Launder and Spalding, 1974), since this model has been found to generate reasonable accuracy for most indoor air flow. Equation (1) and the turbulence model are highly non-linear and self-coupled, resulting in no analytical solutions for air pollutant transportation outdoors. The equations are discretized into algebraic equations by the finite volume method (FVM). The discretization method is a second-order upwind scheme and SIMPLE algorithm is adopted (Patankar, 1980). The Boussinesq model is employed to consider the buoyancy effect (Launder and Spalding, 1974).

This study used a commercial CFD program, Airpak, that has been validated on numerous occasions for outdoor air flow studies. Airpak uses the FLUENT solver engine for thermal and fluid-flow calculations. The solver engine provides complete mesh flexibility, and allows users to solve complex geometries using unstructured meshes. The multigrid and segregated solver algorithms provide robust and quick calculations (Fluent Inc., 2001).

4. TECHNICAL LINE FOR DETERMINING OPTIMAL PLAN

This study adopted CFD simulation to determine optimal plan of Shaoxing road. The overall technical
line can be divided into the following four parts: 1) Calculate the emission rate of vehicles on the road under study, 2) Obtain the meteorological data of Qingdao city for CFD simulation, 3) Predict the influence of the road under study on the surrounding environment, 4) Present improved plan, as shown in Figure 2.

5. DETERMINATION OF CALCULATION CONDITIONS

5.1 Emission rate of vehicles on the road under study

The traffic volume of the road under study is 2000 vehicles per hour. Vehicle emission factor is the number of grams of a pollutant emitted per vehicle per mile. The values of these factors used in this study are listed in Table 1 according to the reference SEPA (2005).

Table 1. Emission factors of light-duty vehicles.

<table>
<thead>
<tr>
<th>Vehicle types</th>
<th>Emission rate of urban road, g/km</th>
<th>Emission rate of expressway, g/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH</td>
<td>CO</td>
</tr>
<tr>
<td>Microbus</td>
<td>1.9</td>
<td>13.5</td>
</tr>
<tr>
<td>Car</td>
<td>2.2</td>
<td>26.5</td>
</tr>
<tr>
<td>Others</td>
<td>3.4</td>
<td>22.6</td>
</tr>
</tbody>
</table>

A moving line source model is adopted in this study to estimate the emission rate of moving vehicles. The equation of this model is given as:

\[ Q_{sp} = \sum_{i=1}^{n} q_{ij} \times l_i \times E_{f_{jw}} \]  

(2)

where \( Q_{sp} \) is the emission rate of pollutant \( w \) from \( j \)-type of vehicle on \( i \)-th road (g/h), \( q_{ij} \) is the traffic volume of \( j \)-type of vehicle on \( i \)-th road, (vel/h), \( l_i \) is the length of \( i \)-th road, (km), \( n \) is the total number of segments divided of certain road, \( E_{f_{jw}} \) is the emission factor of pollutant \( w \) from \( j \)-type of vehicle, (g/km.vel). Submitting the data in Table 1 into Eq. (1), we obtain the emission rate of hydrocarbon (CH), carbon monoxide (CO), and nitrogen oxides (NOx) are 3.15 kg/h, 26.292 kg/h, and 1.554 kg/h, respectively. Therefore, CO is the major component of the pollutant emitted from various vehicles.

5.2 Meteorological data

Meteorological data of Qingdao city are summarized in Table 2.

5.3 Parameters of atmospheric boundary layer

Atmospheric boundary layer parameters of Qingdao city are summarized in Table 3 according to Fluent Inc. (2001).
Table 3. Parameters of atmospheric boundary layer

<table>
<thead>
<tr>
<th></th>
<th>Meteorological Station</th>
<th>Desired Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain factor</td>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td>Boundary layer thickness</td>
<td>270 m</td>
<td>370 m</td>
</tr>
<tr>
<td>Surface roughness height</td>
<td>0.3 m</td>
<td>0.3 m</td>
</tr>
</tbody>
</table>

6. RESULTS AND DISCUSSIONS

From the results in the section 5.1, we can see that CO is the major component of the pollutant emitted from various vehicles. Therefore, this study selects CO as a representative pollutant and takes the distribution of CO around the road as a standard to weigh one plan against another.

Fig. 3. Comparison of the distribution of CO under summer prevailing wind direction between initial plan and final plan (Coordinate X is the north direction).

Fig. 4. Comparison of the distribution of CO under winter prevailing wind direction between initial plan and final plan (Coordinate X is the north direction).
In this study, we have simulated a lot of tentative plans to achieve the optimal one within the range of various possibilities. Here, we only select two plans, the initial and final plans, from them for the purpose of demonstration. The major difference between these two plans is that the road surface is at the level of ground for the initial plan while 10 m below the ground for the final plan.

The distributions of CO for two plans under the prevailing wind direction of summer are represented in contour plot, as shown in Fig 3. Under the prevailing wind direction of winter, Fig 4 shows a comparison of the distributions of CO between the initial and final plan.

From the Figs. 3 and 4, we can find that the concentration of CO around the road for final plan is obviously lower than that for initial plan. According to the national standard SEPA (1996), the threshold value of average concentration of CO for ambient air is 4 mg/m3. Therefore we define a perpendicular distance from the road to the contour line at 4 mg/m3 as influence distance. By further calculating, we obtained the maximum influence distance for different plans in different seasons. On the one hand the maximum influence distance for the initial plan is 150 m while that for final plan is only 30 m in summer, on the other hand this distance for the initial plan is 120 m while that for final plan is only 20 m in winter. Thus it can be seen that the influence of road on the surrounding environment is remarkably reduced for adopting the final plan.

In addition, we can find that the influence range of exhaust pollutant in summer is considerably larger than that in winter by comparing Fig. 3 and Fig. 4. This reason for this phenomenon may well be that the angle between the prevailing wind and the road in summer is larger than that in winter. Consequently, for reducing the influence of road on surrounding environment, we should reduce this angle as much as possible. In particular, we should avoid the situation in which the prevailing wind direction is at a right angle to the road.

7. CONCLUSIONS

This study combines fundamental theory of underground space planning with CFD simulation to optimize the planning and designing of a sunken road in China. The results of CFD modeling provides a basis for quantitively evaluating the influence of sunken road on surrounding environment, and also provides useful lessons for many similar underground projects. From the results of this study, the following conclusions could be drawn:

1) The final plan is considerably superior to the initial plan in this study since we have employed CFD simulation in the planning and designing stage. By adopting the final plan, we could substantially reduce the influence of road on the surrounding environment.

2) The prevailing wind direction should be fully considered in the planning and designing stage of sunken road. In addition, we should try to reduce the angle between the prevailing wind and the road and to avoid the situation in which the prevailing wind direction is at right a angle to the road.

REFERENCES