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THESIS

-SUMMARY-

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STUDY OF VENTILATION SYSTEMS OF UNDERGROUND STRUCTURES FOR THE PURPOSE OF THEIR PREPARATION TO PREVENT THE CONSEQUENCES OF SOME MAJOR ACCIDENTSAND OF TERRORIST ACTS WITH AEROSOLS

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1. Concepts, definitions, motivation of the thesis, objectives pursued

The thesis "Study of ventilation systems of underground structures in order to prepare them for the prevention of consequences of major accidents and terrorist acts with aerosols" develops a highly topical subject of study in the modern era, presenting a way of applied research harmonized with current requirements from the perspective of assessing the degree of vulnerability of underground spaces of public interest, in particular from the point of view of ventilation installations, which have not been designed to cope with terrorist attacks (with hazardous substances of explosive and/or toxic combat/harmful nature), as well as possible major accidents.

The theoretical and practical basis for the development of the methodological infrastructure for the study of ventilation systems of underground structures in order to prepare them for the prevention of the consequences of major accidents and terrorist acts with aerosols involved the following research steps:

-Analysis of the main international and national regulations concerning hazards that can generate significant undesirable events of a major nature due to hazardous substances of an explosive and or toxic nature;

-Analysis of fluid dynamics and computer simulation solutions for ventilation networks;

-Investigation of methods for preventing and fighting fires in road tunnels;

-Developing a technical solution to prevent the spread of combustible products in tunnels by implementing a divisible system;

-To carry out experimental laboratory tests and CFD simulations on the dynamic behaviour of explosive and/or toxic substances in closed spaces;

-Development of a simplified method for risk assessment in one-way road tunnels for road transport of dangerous goods;

-The technical-scientific basis of a prospective and exploratory tool for modelling, assessing and managing the risk of terrorism specific to underground transport infrastructure.

The motivation of the PhD thesis is related on the one hand to the usefulness and ease of performatization/improvement of the methodological mechanism for preventing and fighting fires in road tunnels with the possibility of its realization through the implementation of a "divisible system", and on the other hand to the configuration of methodological tools of good practice in the field of securing the transport of dangerous goods by road in unidirectional road tunnels, as well as the modelling/assessment/management of the risk of terrorism specific to these types of technical infrastructure, ensuring the orientation and unified guidance of policies

and strategies for the effective management of a predictable and sustainable quality of security of the spaces related to underground structures of public interest intended for transport.

The main objectives of the thesis are to carry out technical-scientific research for the study of ventilation systems of underground structures in order to prepare them to prevent the consequences of major accidents and terrorist acts with aerosols, respectively: development of a technical solution for the prevention of the spread of combustible products in tunnels by implementing a divisible system; carrying out experimental laboratory tests and CFD simulations on the dynamic behaviour of explosive and or toxic substances in closed spaces, together with the conceptualisation of the risk assessment mechanism specific to unidirectional road tunnels for the transport of dangerous goods by road that can make these types of structures dedicated to public utility transport vulnerable; configuration of best practice methodological tools in the field of modelling, assessment and management of the risk of terrorism specific to underground transport infrastructure. These core objectives are met through derived objectives, namely: study of the main international and national regulations on major hazards due to hazardous substances of explosive and/or toxic nature (European SEVESO Directives, Explosives Directive 2014/28/EU, Law 59/2016, etc.); summary presentation of Law 277/2007 on minimum safety requirements for tunnels located on national sections of the trans-European road network; conceptualisation of the fluid flow phenomenon; generic description of specialised software used in the field of ventilation of underground transport structures; presentation of general aspects of existing road tunnels at European and international level, as well as fire fighting concepts and methods; carrying out various CFD simulations on: dynamic behaviour of methane in enclosed spaces/ accumulation-evacuation dynamics of oxide and carbon dioxide in enclosed spaces; development of a technical solution for the prevention of the spread of combustible products in tunnels by implementing a divisible system; development of a simplified method for risk assessment in unidirectional road tunnels concerning the transport of dangerous goods by road; modelling, assessment and management of the risk of terrorism specific to underground transport infrastructure.

The derived objectives are met based on the primary objectives, namely: study of the literature by consulting the main bibliographical references in the field of interest of the thesis; description of the laws governing fluid flow with emphasis on highlighting: flow phenomena, static/dynamic/total pressure, incompressible flow limits, basic laws used in the field of ventilation/aeration of underground transport structures, determination of the friction factor and resistance of underground structures; computer simulation of ventilation networks together with a summary presentation of specialised computer applications for solving problems in the field

of ventilation/aeration of underground transport structures; development of methodological solutions for preventing and fighting fires in road tunnels; general considerations, laboratory experiments and discussions on CFD simulation of the dynamic behaviour of methane, as well as carbon monoxide and carbon dioxide accumulation-evacuation in enclosed spaces; implementation of a divisible system for the prevention of the spread of combustible products in tunnels; modelling of terrorist attack scenarios, analysis and risk assessment of the terrorist threat, as well as crisis management generated by the dangers of malicious actions and case study.

The research strategy to achieve the objectives of the thesis focused on four main technical-scientific horizons, namely:

- The work begins with a synthetic presentation of the main regulations applicable at international and national level in the field of major accident risk specific to underground transport structures, which establish normative technical aspects regarding their securing in order to prevent the consequences of major accidents and terrorist acts with dangerous substances of explosive and/or toxic nature;

- The next step in the research focuses on the study of fluid dynamics and computer simulation solutions for ventilation networks, as well as on the establishment of technical solutions for preventing and fighting fires in road tunnels, and on the analysis of the results of experimental laboratory tests and CFD simulations on the dynamic behaviour of explosive and/or toxic substances in enclosed spaces;

- Another important step of the research lies in the expression of contributions on the development of a simplified method of risk assessment in one-way road tunnels for the transport of dangerous goods by road, together with the modelling, assessment and management of the risk of terrorism specific to these technical facilities of public interest.

2. Thesis structure and some contributions

Structurally, the work comprises an introductory chapter with a characteristic theme and 6 chapters of content, plus a final chapter of Final Conclusions and personal contributions, totalling 190 pages, of which 175 pages represent the thesis itself and 14 pages represent the Bibliography which has a total of 226 bibliographical notes and specialised Annexes which facilitate a better understanding of the thesis and its objectives.

Among the author's main contributions that are documented in the chapters of the thesis are:

- The carrying out of an integrated study through which the national and international legislative framework has been identified that allows the predictable safe operation of major accident risk activities carried out in underground transport structures;

- Conceptual and applied analysis of fluid dynamics and computer simulation solutions for ventilation networks;

- Investigation of fire prevention and fighting methods in road tunnels;

- Development of a technical solution to prevent the spread of combustible products in tunnels through the implementation of a divisible system

- Carrying out experimental laboratory tests and CFD simulations on the dynamic behaviour of explosive and/or toxic substances in closed spaces;

- Development of a simplified method for risk assessment in unidirectional road tunnels for road transport of dangerous goods;

- Scientific-technical basis of a prospective and exploratory tool on modelling, assessment and management of terrorism risk specific to underground transport infrastructure.

The valorisation of the technical-scientific results of the research carried out was achieved through their dissemination in papers, conference/symposium proceedings or ISI or BDI indexed journals, as per Annex 1.

3. Summary of work

The elaboration of scenarios for the occurrence of an undesirable event resulting in a major accident involving the presence of hazardous substances of an explosive and/or toxic nature in underground spaces of public interest (e.g. networks of tunnels and metro stations, as well as other underground spaces of public utility) requires an analysis of the degree of vulnerability, in order to determine a rapid response to prepare, protect and mitigate the foreseeable consequences of the occurrence of undesirable events with major impact.

The PhD thesis entitled Study of ventilation systems of underground structures in order to prepare them for the prevention of the consequences of major accidents and terrorist acts with aerosols comprises 8 chapters summarised below.

Chapter 1, Introduction outlines the general considerations, the main and specific objectives, the motivation of the thesis and a brief summary of the work.

In Chapter 2, entitled Analysis of the main international and national regulations on major accident hazards and in the field of safety of tunnels located on national sections of the trans-European road network, I have presented a summary of the main regulations applicable

at international and national level in the field of major accident hazards applicable to economic operators active in the management and safety of underground "tunnel" type structures present on the trans-European road network.

Thus, the technical requirements for the major risk management system have been analysed and documented, which have been regulated both at European and national level by a series of European directives and laws transposing them (Seveso directives, HG 804/2007, HG 79/2007, Law 59/2016) concerning the appropriate management of major accident hazards involving hazardous substances.

Regulatory measures have also been documented to ensure a minimum level of safety for users of tunnels located on the national sections of the Trans-European Road Network, by preventing the occurrence of critical events that could endanger human life, the environment or tunnel installations and by ensuring protection in the event of accidents.

Chapter 3, Fluid Dynamics Analysis and Computer Simulation Solutions for Ventilation Networks, presents a series of theoretical contributions on the analysis of the laws governing air flow from the perspective of conceptualising the fluid motion problem and the basis of characteristic parameters for the analysis and evaluation of ventilation networks related to dedicated ventilation systems. We have also highlighted at a synthetic level a series of specialized computer applications for computer simulation of dedicated ventilation networks for the design, analysis and operation of ventilation systems.

The aspects related to the Contributions on the development of a technical solution for the prevention of the spread of combustible products in tunnels through the implementation of a divisible system, highlighted in chapter 4, report both general aspects on the existing European/international and national road tunnel infrastructure from a techno-economic perspective (dimensional parameters, construction and inauguration time horizons, traffic safety, number of vehicles transiting/unit of time, investment value, facilities and equipment, etc.), as well as a highlighting of the main established fire-fighting methods based on innovative concepts applied in order to prevent the outbreak/development of these types of undesirable events. We have also developed a technical solution to prevent the spread of combustible products in tunnels by implementing a divisible system. This consists of a simple flexible device that completely or partially blocks the tunnel cross-section, divides the tunnel into short sections and at the same time completely or partially isolates the fire outbreak in sufficient time to save lives.

In Chapter 5 entitled Contributions on conducting laboratory experimental tests and CFD simulations on the dynamic behaviour of explosive and/or toxic substances in enclosed

spaces, we presented the results of the study of the dispersion dynamics of explosive and/or toxic gases (CH4, CO and CO2) using CFD (Computational Fluid Dynamics) technique for modelling their dispersion in an enclosed space, finding the following:

CH4: The methane gas dispersion process in a closed enclosure exhibited 2 distinct stages namely: incubation period, accumulation period and venting period. The methane dispersion process is characterized by a variable evolution in both horizontal and vertical planes. This is proved by the different values of the gas concentrations at the level of the detectors in the same time interval; the incubation period showed values between 18 and 42 minutes; the accumulation period showed evolutions between 46.5 and 73.5 minutes; the period of dispersion and progressive dilution of the gas comprising the incubation and accumulation segments showed evolutions between 84 and 93 minutes; the maximum concentration of methane gas showed a variable evolution with values between 0.4 and 1.15 % Vol. ; The methane gas dispersion and progressive dilution gradient in the closed enclosure, Gd , varied between 0.286 and 0.767 % Vol./h;

CH4: Modelling of methane gas dispersion in the enclosure showed a dispersion phenomenon oriented along the flow direction of the refluxed gas jet. The methane gas flow is in the form of a flat jet stuck to the hearth up to the middle of the enclosure in the flow direction after which it breaks off and tends towards the opposite wall. The gas flow rises up the opposite wall and disperses unevenly at the ceiling; the methane gas concentration is maximum in the source area, gradually decreases by dilution as it moves away from the source and becomes variable and low in the accumulation area at the ceiling. If methane gas were introduced continuously over a longer period of time the atmosphere in the enclosure would be dislocated from the ceiling to the hearth.

CO: The dispersion process of carbon monoxide in the lower level 1 is characterised by a variable evolution. Thus a variation of the specific gas concentrations for the turbulent incipient flow was found at all control points; the carbon monoxide dispersion process at the middle level 2 is characterised by a variable evolution. Thus, a variation of specific gas concentrations for medium turbulent flow was found at all control points; the carbon monoxide dispersion process at the upper 3 level is characterised by a variable evolution. Thus, a variation of the specific gas concentrations for the strongly turbulent flow was found at all control points; The dispersion and progressive dilution gradient of carbon monoxide at the level of the closed enclosure, Gd , showed a variable evolution depending on the position in the plane of the control points as follows: The gas dispersion and progressive dilution gradient, Gd, at lower level 1 showed values between 2,144 and 2,689 ppm/h; The gas dispersion and progressive dilution

gradient, Gd, at middle level 2 showed values between 1,806 and 2,710 ppm/h; The gas dispersion and progressive dilution gradient, Gd, at upper level 3 showed values between 2,108 and 3,270 ppm/h.

CO: Modelling of carbon monoxide dispersion in the enclosure showed a dispersion phenomenon oriented along the flow direction of the refluxed gas jet. The flow of carbon monoxide has the form of a flat jet stuck to the hearth up to the opposite wall. The gas flow rises vertically up the opposite wall and disperses uniformly at ceiling level. The carbon monoxide concentration is highest in the source area, gradually decreases by dilution as it moves away from the source, and becomes relatively uniform and low in the accumulation area throughout the enclosure. If the carbon monoxide were introduced continuously over a longer period of time the atmosphere in the enclosure would have relatively uniform concentrations throughout the enclosure.

CO2: The dispersion process of carbon dioxide in the lower tier 1 is characterised by a variable evolution. Thus, a variation in gas concentrations specific to turbulent incipient flow was observed at all control points. The flow becomes laminar as the flow process stabilizes; the carbon dioxide dispersion process at mid-level 2 is characterized by a variable evolution. Thus a variation of the specific gas concentrations for the turbulent medium flow was observed at all control points. The flow becomes incipiently turbulent as the flow process stabilises; the carbon dioxide dispersion process at upper level 3 is characterised by a variable evolution. Thus, a variation of specific gas concentrations for strongly turbulent flow was found at all control points. The flow becomes laminar as the flow process stabilizes; the dispersion and progressive dilution gradient of carbon dioxide at the level of the closed enclosure, Gd , showed a variable evolution depending on the in-plane position of the control points as follows: The gas dispersion and progressive dilution gradient, Gd , at lower level 1 showed values between 4.217 and 4.526 % Vol./h; The gas dispersion and progressive dilution gradient, Gd , at middle level 2 showed values between 1.717 and 1.855 % Vol./h; The gas dispersion and progressive dilution gradient, Gd , at upper level 3 showed values between 0.088 and 0.092 % Vol./h.

CO2: Modelling of carbon dioxide dispersion in the enclosure showed a dispersion phenomenon oriented along the flow direction of the refluxed gas jet. The flow of carbon dioxide has the form of a flat jet stuck to the hearth up to the opposite wall. The gas disperses non-uniformly vertically from the glass. The concentration of carbon dioxide is maximum in the source area, gradually decreases by dilution as it moves away from the source, and becomes relatively uniform and low in the accumulation area at the glass level. If methane gas were

introduced continuously over a longer period of time the atmosphere in the enclosure would be dislocated from the hearth to the ceiling.

Chapter 6 - *Contributions to the development of a simplified method for risk assessment in unidirectional road tunnels for the transport of dangerous goods by road*, outlines a simplified method for estimating the level of risk in unidirectional road tunnels, which provides the possibility to estimate the level of risk, expressed in terms of aspected value, as a function of tunnel length, average daily lane traffic, percentage of both heavy goods vehicles and dangerous goods vehicles. The proposed method could assist the competent authorities in the field in making more appropriate decisions on traffic control strategies when the risk due to peak hours of traffic volume, including especially dangerous goods vehicles, is considered to be excessive compared to normal standards. In this respect, in order to reduce the level of risk, the authorities could allow dangerous goods vehicles to transit through the tunnel at night and/or under escort, or an alternative route running completely in the open could be tested.

Chapter 7 - *Contributions on the technical-scientific underpinning of a prospective and exploratory tool on modelling, assessing and managing terrorism risk specific to underground transport infrastructure*, conceptualises in the first part the principles on which a holistically configured tactical and strategic roadmap for modelling, assessing and managing terrorism risks specific to cyber, physical and organisational infrastructures should be based, taking into account the complex nature of terrorism risk assessment and management in which all relevant threats, costs and benefits need to be analysed in a multi-objective framework, and then summarising the essential aspects of the need for a technical-scientific basis for a methodological mechanism for effective terrorism risk management in order to make appropriate use of the means of eradicating this scourge which is continuously affecting modern society. In this respect, effective management of the risk of terrorism requires appropriate management of the identification and analysis of threat factors, with a view to the objective determination of the corresponding risks on an appropriate technical-scientific basis, using established methodologies for the most accurate modelling of terrorist event scenarios with extremely severe consequences.

Chapter 8 entitled *Final conclusions and personal contributions* highlights the contributions made to the development of the infrastructure for analysing and assessing the risk of a major accident generated in underground structures, taking into account acts of maliciousness that can result in aerosol terrorist actions with extremely severe consequences, respectively: conceptualisation and configuration of methodological mechanisms for the analysis and assessment of major accident risks specific to underground transport structures,

including systemic vulnerabilities generated by acts of ill will; analysis and risk assessment of specific operations of containment constructions (rapid closure systems) in underground transport infrastructure; development of an innovative methodological tool for assessing the degree of safety at work specific to underground transport infrastructure construction activities; technical-scientific basis for a prospective and exploratory tool for modelling, assessing and managing the risk of terrorism specific to underground transport infrastructure.

4. Personal contributions

4.1.-Theoretical contributions

The theoretical contributions, documented in the paper, which are of major technical-scientific importance are:

-The completion of an integrated analysis through which the national and international legislative framework has been identified that allows the safe and predictable deployment of major accident hazards specific to underground transport structures;

-The completion of a synthesis study which highlighted the correspondence between national and international regulations applicable in the field of analysis and assessment of the risk of major accident generated at the level of underground transport structures taking into account acts of terrorism, thus creating the premises for the creation of a particularly useful guide for economic operators and authorities with activity and powers in this field, facilitating optimal decision-making when integrated security of these facilities of urban and industrial utility is required;

- Analysis of fluid dynamics and computer simulation solutions for ventilation networks;

- Conceptual study of fire prevention and fighting methods in road tunnels;

- Development of a technical solution to prevent the spread of combustible products in tunnels by implementing a divisible system;

- Development of a simplified method for risk assessment in unidirectional road tunnels for the transport of dangerous goods by road;

-Modelling terrorist attack scenarios;

-Terrorist threat risk analysis and assessment;

-Managing crisis situations generated by the dangers of malicious actions.

4.2.-Experimental and applied contributions

The experimental and applied contributions documented in the thesis, which are of significant value from a technical-scientific point of view, are:

-Simulation of fire development scenarios of different powers of 5, 10, 30 and 50 MW in tunnels with different slopes of 0, 1; 3, 4 and 6.0%;

-Simulation of CFD on the dynamic behaviour of methane in confined spaces;

- CFD simulation of carbon monoxide accumulation-evacuation dynamics in closed enclosures;

-CFD simulation of carbon dioxide accumulation-evacuation dynamics in closed enclosures;

-Case study with application examples on assessing and combating the risk of terrorist attack on underground transport structures.

Future research directions

Taking into account the contributions expressed in the thesis and the specific issues addressed in the thesis, the following future research directions can be exemplified:

- Design and implementation of novel security systems with artificial intelligence (biometric fingerprint recognition, etc.) related to existing facilities at the level of underground transport structures present on road networks;

- Performatisation of integrated monitoring equipment for urban sites with underground public utility transport structures equipped with specialised state-of-the-art devices (spectro-drones) dedicated to the exploration/examination/survey/zoning of spaces within these infrastructures;

- Setting up intelligent underground transport structures equipped with modern devices and dedicated specialised software for operational and interactive supervision of the total safety status of the transit of these types of technical facilities for urban and industrial transport, including dangerous goods.