Dimensioning physical protection barricades against the propagation of pressure waves following a detonation

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Résumé – Depuis quelques années, la France doit faire face aux risques d'explosion d'origine accidentelle ou intentionnelle présents sur son territoire comme en opération extérieure (OPEX). La lutte contre ces risques repose sur l'évaluation de la menace, la conception de mesures de prévention (pour éviter l'événement redouté) et la mise en place de barrières physiques de protection dans le but de protéger les intérêts français, les sites industriels et les biens et les personnes, contre les éclats, les effets thermiques et les effets mécaniques de l'onde de souffle consécutifs à une explosion. En France, la réglementation définit des normes issues de « bonnes pratiques » pour l'industrie pyrotechnique concernant les zones de dangers situées derrières ces barrières, dites « zones des effets létaux significatifs » ; il reste cependant à déterminer comment l'onde se propage et se reforme dans les installations industriels à géométrie complexe. De plus, ces normes ont été établies à partir de résultats pour des détonations d'explosifs chimiques condensés. A l'heure où les industriels doivent appliquer les Plans de Prévention des Risques Technologiques (PPRT), non seulement il n'existe pas d'outils de dimensionnement d'une barrière physique de protection permettant de protéger des installations sensibles et leur environnement contre des explosions d'origine intentionnelle ou accidentelle, mais les données qui permettraient de le faire sont encore largement à produire. L'objectif du programme BARPPRO (dimensionnement des BARrières Physiques de PROtection contre la propagation d'ondes de souffle consécutives à une explosion), au cœur des préoccupations françaises de la sécurité des biens et des personnes, vise à définir des moyens de dimensionnement des barrières physiques de protection et à évaluer leur efficacité pour atténuer les effets de pression consécutive à une détonation. Les études qui seront réalisées seront à la fois expérimentales, numériques et théoriques. La connaissance acquise sera transcrite dans un guide méthodologique utilisable pour le dimensionnement pratique des barrières physiques de protection.

Abstract – At present, France is confronted with both accidental risks and an increasing risk of malevolence not only on national territory but also during international operations (OPEX). The fight against these risks relies mainly on the evaluation of the threat, the implementation of preventive measures (to avoid the event) and the installation of physical protection barriers that limit the harmful consequences of an explosion, such as blast waves, thermal shock, fire missiles and fragments, in the scope of protecting French interests, industrial sites, the environment, people, infrastructure and habitats. In France, the regulation stipulates standards for the pyrotechnics industry regarding the danger areas located behind physical protection barriers. Many factors remain unknown, which makes it difficult to establish these standards in the pyrotechnical field. This difficulty in establishing the applicable standards is a serious issue for the industrialists who must conform to the Prevention Plans of the Technological Risks (PPRT). Indeed, there are no tools that would aid in the design of a physical protection barrier to protect the vulnerable installations and their environment against intentional or accidental explosions. Experimental and numerical data must be obtained to further our ability to construct such barriers. The objective of the BARPPRO project (Physical dimensions of Protection BARriers against pressure wave PROpagation Following an Explosion) is to define how to design protection barriers that limit the propagation of blast waves in an explosion and to assess the ability of these barriers to reduce the harmful consequences of an explosion. Experimental, numerical and theoretical studies will also be performed for this purpose. The insights gained from this project will be presented in a methodological guide for the practical use of physical protection barriers.

1. Introduction

1.1 Context

This research project is aimed at improving the safety of individuals and property, which is a global concern. In particular, this research considers the protection of hazardous industrial facilities from intentional and accidental explosions. These industries, particularly those referred to as "Seveso", are characterised by a high hazard potential that could be "liberated" in the event of a failure or violent attack (such as an explosion). Beyond the necessary preventive measures (e.g., design, monitoring and control), additional measures are needed to protect the sensitive areas of these facilities to reduce the identified risks to an acceptable level. Thus, this research considers the protection of sensitive industrial facilities against attacks caused by external or internal explosions that are either intentional or accidental in nature. Specifically, this research focuses on the use of physical barriers as a means of protection against the effects of explosions, including the secondary projection of fragments via pressure waves. This topic is sometimes considered under the control of major risks (particularly for the most serious scenarios) which is not always implemented in a comprehensive manner. The objective of the project is to identify ways in which these physical barriers can be designed. Experimental, numerical and theoretical studies have been conducted on basic and applied industrial vocation. The insights gained from this research will be presented in a methodological guide for the practical use of physical protection barriers.

1.2 Objectives

In the case of pressure waves resulting from an explosion, the establishment of physical protection barriers would reduce the effects of distance (and thus the extent of the exclusion zone around the facility), the potential damage to individuals and property, and thus the cost of a risk prevention policy for hazardous installations. This technique is used in the control of major risks and more severe scenarios in particular. If the implementation of these barriers (which significantly limits their use) is not more fully understood and their design criteria are not so well established, then such measures could not be recommended for a variety of industrial sites.

The existing literature has shown that a physical protection barrier can effectively reduce the rate of loading by a blast wave and can protect structures when they are close to the screen. However, the effect of these barriers has not yet been quantified for various types of explosions and barrier geometries, and the scope of this protection downstream of the barrier has not been established. This lack of quantification is the reason for which the existing literature has not proposed an analytical expression characterising the effect of a blast wave on the structures behind a protective physical barrier or determined the generic sizing of a barrier.

The objective of this project is to advance our understanding of the propagation of pressure waves from an external explosion (accidental or intentional) around a physical barrier protection.

The proposed methodology is based on a coupled approach of simulations and experiments. The experiments, which were carried out on small and medium scales, are used to validate numerical models that will establish the rules to be observed for the full-size design of a physical protection barrier.

This study aims to understand the physical phenomena of blast wave propagation around a physical protection barrier (propagation of waves arriving at a barrier face and bypassing the edges and top of the barrier, wave reflection due to buildings behind the screens) to define a guide for the geometric design of such barriers. Then, the ability of the designed barriers to reduce the effects of a blast wave resulting from a downstream explosion or detonation is evaluated.

This project considers the two regimes that can occur after an explosion, detonation. However, this article focuses exclusively on detonation. The propagation of the shock wave resulting from the detonation both upstream and downstream of the barrier is considered. Thus, the phenomena present during the interaction of a shock wave with a barrier of protection are identified to understand how their coupling leads to the appearance of a protective zone or an increase in certain characteristics of the shock wave.

After a brief summary of the existing literature, the experimental and numerical approaches used in this project are presented, followed by an analysis of the most important phenomena encountered. The barrier is considered to be perfectly rigid in this investigation.

2. State of the art

The existing research pertaining to different configurations of obstacles, including walls, barricades, and other configurations, is summarised here. Previous studies have established the same conclusion, namely, that a protective barrier is only effective under certain conditions and the following predefined settings: size of the load (W); height (H) and width (e) of the barrier; top of the obstacle angle to the ground barriers (α); and distance between the charge and barrier (d).

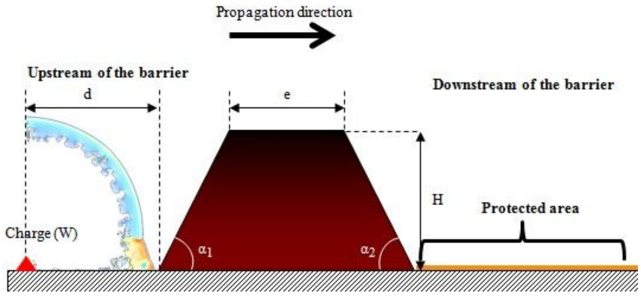

FIG. 1 : representative protection barrier

The experimental work of Allain (1994) and the numerical studies of Borgers (2010) have obtained different findings for this type of structure without a thickness at the top (e = 0 m) and with one or two 45-degree slopes. These studies have shown that the reflection on the upstream side (facing the explosion) can be regular or Mach, is followed by rarefaction waves, the reflection is continued on the downstream face (rear), which accelerates the front and the reflection on the ground, thus increasing the pressure. The evolution of the pressure throughout the propagation of the shock wave does not obey a linear function in terms of the distance from the centre of the explosive charge. Therefore, the protective effects of the barrier are dependent on its geometry (e.g., length and thickness at the top corners of the upstream and downstream sides).

The Guide to Best Practices in Pyrotechnics (Guide de Bonnes Pratiques en Pyrotechnie) has reported some of NATO's recommendations on the design of a barricade. For instance, the height of the barrier must extend at least 2 meters above the highest pile of explosives, the thickness must be a minimum of 0.50 meters at the crest of the barrier and the length must exceed that of the battery by at least 2 meters on each end.

3. Approaches

3.1 Experimental approach

Small-scale experiments were performed using a well-established process in the PRISME laboratory [4]. The set-up consists of a horizontal table on which the barrier and explosive charge is placed. The gaseous mixture (C_3H_8+$5O_2$) is held in a container whose aqueous hemispherical radius R_0 is selected by the experimenter. The gas mixture is detonated by electric power supplied through an exploding wire. Piezoelectric pressure sensors are regularly arranged upstream and downstream of the barrier [5]. Pressure sensors are also placed on the opposite side of the barrier close to the load to ensure the reference measurement in free field. This study adopted a 1/15th scale. The design of the barrier was determined by applying the similarity Hopkinson's law. Thus, for an explosive with a full-scale mass M (1/1) arranged at a distance R and with a measured pressure ΔP^+ and impulse I^+, at the small scale (1/k), the mass of gas is k^3 x M, the overpressure is ΔP^+, and the impulse is k x I^+ if the load is at a distance k x R. Similarly, the geometric characteristics of the barrier are assigned by the coefficient k. As a comparison, for the scale factor employed here, a spherical propane-oxygen radius R_0 = 0.06 m is equivalent to 3.4 kg of TNT at a scale of 1. Two charges of gas are used for radius of 0.06 m and 0.03 and positioned 0.07, 0.085 and 0.01 m upstream of the barrier. The following table summarises the barrier configurations studied here. The dimensions are in accordance with the recommendations of NATO [3] and the frame thresholds.

TAB. 1: Dimensions of the barriers considered in this experimental study

Barrier	1	2	3	4	5	6
Height (m)	0.19	0.19	0.16	0.19	0.19	0.19
Thickness at the top (m)	0.03	0.03	0.06	0.19	0.19	0.19
Length (m)	0.80	0.40	0.80	1.30	1.30	0.40
Downstream angle α_1	45	45	45	45	90	90
Upstream angle α_2	45	45	45	90	45	45

3.2 Numerical approach

The experimental configurations were simulated numerically using the solver HERA [6] on the computing platform TERA CEA-DAM (140,000 processors). HERA is a multi-physics software that is used to simulate the detonation of any explosive (CHON explosive (TNT) or gaseous explosive (propane-oxygen)). The software is a Eulerian hydrocode with Godunov's scheme and Adaptive Mesh Refinement (AMR) capabilities. AMR manages the mesh refinement depending on the blast wave propagation. To limit the number of meshes and reduce the time required for calculations, a study was conducted to compare the simulation results obtained with 2D-axisymmetric geometry and 3D geometry for the same mesh size. The 2D axisymmetric geometry creates a cannon effect downstream of the barrier leading to an overpressure that is up to 10% higher than those obtained with the 3D geometry. However, this difference is of the same order of magnitude as the experimental uncertainty. The configuration will be used to simulate the short barrier in the 3D simulations (0.40 m, see Tab. 1).

4. Analysis

The phenomena analysis was conducted from the simulations validated experimentally. This analysis can be described in the three steps of propagation of the shock wave: 1) on the upstream side, 2) on the top, 3) and on the downstream face and downstream of the barrier.

The incident shock wave generated by the detonation of the charge gas impacts the upstream side of the barrier and is reflected. Reflection of the incident wave can be regular or Mach. The reflected wave propagates in a medium composed of two zones, the burned gases (detonation products) and air. At the interface between these two zones, a wave is transmitted in the burned gases and another is transmitted in the air. The latter catches the incident shock wave and results in recombination around the wave reflected on the original interface. The detonation products create increased pressure and impulse on the upstream side of the barrier. A critical distance can be determined based on the geometry of the barrier, the nature of the explosive charge and its mass.

Rarefaction waves occur at the top of the barrier. The greater the thickness of the top of the barrier, the more important the effect of relaxation is in reducing the pressure. Furthermore, a second expansion occurs on the downstream corner of the top of the barrier. Relaxation then continues on the downstream face. The wave arriving at the base of the barrier continues to propagate and is reflected on the ground. The amplitude of the reflected wave and the nature of the reflection depend on the history of the wave and the geometry of the downstream barrier (height and angle α_2). As the angle α_2 increases, the angle of deflection of the rarefaction wave increases and the pressure decreases.

In the case of a small barrier (L = 0.4 m), the waves from the side faces are combined with that from the top, leading to the formation of a Mach stem and an increase in pressure downstream of the barrier (FIG. 2).

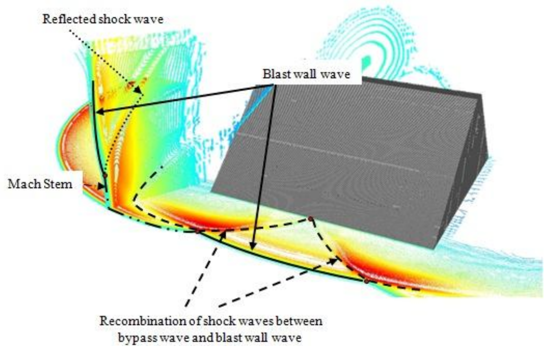

FIG. 2: Recombination of blast wave behind the barrier

5. Conclusions and Perspectives

This analysis shows that the design of the barrier and its location upstream of the explosive charge depends on the area to be protected (immediately downstream at the base or further downstream of the barrier). In general, the configurations considered here indicate that the protective effect is greater when the barrier is close to the load and correspond with the findings of Allain [1] and Borgers [2]. The NATO recommendations did not specify the angles of the barrier or the distance between the charge and barrier.

The results obtained by numerical simulations in 2-D asymmetric geometry (parametric study) for a charge of TNT were used to shed light on the evolution of the maximum overpressure and positive impulse at the ground and at a man's height. This study analysed 3,125 protective barrier configurations and required the equivalent of 16 million hours of computing equivalent uniprocessor.

The proposed guidelines are currently being applied to industrial configurations, and future research topics include investigation of the storage configuration (presence of storage tanks), medium scale testing and modelling of the Billy-Berclau accident (France, 2003).

This study highlights the physical phenomena that can only be investigated analytically. In conjunction with this study, a theoretical coupling of different physical phenomena is underway to define an analytical approach to calculate the characteristics of the shock wave, with an accuracy of +/-20% around the barrier depending on its geometry.

6. Acknowledgements

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References

[1] L. Allain, *Barricade influence on blast wave propagation*. SNPE / Division Defense and Space, private communication, 1994.

[2] J. Borgers, *Blast walls reviewed*. 21st Military Aspect of Blast and Shock (MABS), Jerusalem, October 4-8th 2010,

[3] GBPP , *Guide de Bonnes Pratiques en Pyrotechnie* , Guide SFEPA, n°9 version n°1-A du 13/02/2009.

[4] S. Trélat, I Sochet I., B. Autrusson, K Cheval, O. Loiseau. *Strong explosion near a parallelepipedc structure*. Journal Shock Waves V.16, 4-5, 349-357 , 2007.

[5] S. Eveillard, I. Sochet, J-Y. Vinçont. *Propagation of blast wave in presence of blast wall.*22st Military Aspects Blast and Shock (MABS), Bourges, November 4-9th 2010.

[6] H. Jourdren. *A Hydrodynamic AMR Platform for Multi-Physics Simulations, Adaptive Mesh refinement – Theory and Applications*. Lecture Notes in Computational Science and Engineering, volume 41, part III, pp 283-294, 2005.

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