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Large-Scale VCE Consequence Modeling for Industrial Facility Siting, Risk Assessment, Hazard Mitigation Design, and Response Planning

Qiguo Jing*, Ph.D., Brian Holland, Tiffany Gardner#, Yumna Moazzam, and Weiping Dai, Ph.D., CM, P.E.
Trinity Consultants Inc. Dallas, TX 75251, USA (972) 661-8100

* Presenter, E-mail: qjing@trinityconsultants.com

Communication Author, E-mail: tgardner@trinityconsultants.com

Abstract

New, fully three dimensional, technologies are now making it possible to more quickly and accurately simulate and predict the consequences of accidental releases leading to vapor cloud explosions (VCE) at a wide variety of industrial facilities. The primary objective of these explosion consequence analysis (ECA) technologies is to assess building damage and occupant injury levels for both 'individual' and 'all possible' release and explosion scenarios. A typical industrial facility can have hundreds of potential release scenarios and hundreds of potential VCE locations leading to an exponential number of possible explosion scenarios.

High speed 3D modeling techniques can provide updateable, on-going and real-time capabilities for analyzing individual and all possible release and explosion scenarios. These ECA technologies, combined with release probabilities, make possible quantitative risk assessments (QRA) which lead to better risk evaluations, mitigation strategies, risk management, and emergency response planning.

In this paper, the Vapor Cloud Explosion Damage Assessment module in BREEZE ExDAM is used to demonstrate a high speed 3D modeling technique that can quickly 1) generate 3D models of large-scale chemical/petroleum facilities with hundreds of building structures, hundreds of release locations, and hundreds of congestion zones, 2) simulate, display, and document the consequences of individual release scenarios involving a subset of congestion zones within a single plume geometry, and 3) compute, display, and document the maximum consequence levels resulting from explosions at all identified congestion zones.

Introduction

Failure to identify and mitigate explosion hazards is a persistent cause of industrial accidents, impacting sites ranging from fertilizer storage facilities [1] to refineries. While some ECA are performed to comply with regulatory requirements or industry-specific process safety standards [2] [3] [4], in many cases the potential for loss of life and property damage is overlooked until a tragedy occurs. Explosion Consequence Modeling (ECM) can provide detailed information about the possible effects of a blast, and can be used to identify and design mitigation measures. The two traditional ECM techniques have been: 1) basic phenomenological models that are very cost-effective but provide very simplistic results, and 2) computational fluid dynamics (CFD) techniques which provide great detail but are time consuming and can be prohibitively expensive. Many facilities are in need of a detailed ECM analysis to identify and mitigate explosion hazards, but require a moderate approach that can provide detailed damage and injury predictions without the high costs of CFD modeling.

The Explosive Damage Assessment Model (ExDAM), originally developed by Dr. Frank Tatom and marketed as part of Trinity Consultants' BREEZE® Software, expands on the basic phenomenological model concept by adding the ability to model damage and injury while accounting for the structural details of buildings as well as the shielding effect of structures and equipment on the area behind them. Thus, ExDAM provides the safety benefits of a detailed ECM study to a much wider range of facilities at risk from either conventional high explosive (HE) materials or VCE [5].

In this paper we will describe ExDAM's VCE model, VExDAM, discuss the characteristics and capabilities of the model and demonstrate a fast and efficient demonstration simulation of a large-scale VCE in an industrial facility.

ExDAM Explosion Models

ExDAM provides a phenomenological method to predict damage and injury levels for open-air explosions. Historically, since the mid-1980s, organizations involved in the development of this method include the Strategic Defense Command, U.S. Army Corps of Engineers, Southwest Research Institute, Facility Army System Safety (FASS) Office, the Naval Civil Engineering Laboratory, Engineering Analysis, Inc. (EAI), and BREEZE Software / Trinity Consultants, Inc.

The predecessors to HExDAM, the Nuclear Damage Assessment Model (NDAM) and the Enhanced Nuclear Damage Assessment Model (ENDAM), were originally developed to predict large-scale structure damage for nuclear blasts using the Physical Vulnerability System (PVS) [6]. The mathematical and computational aspects of this system are provided in a companion public/unclassified document [7]. ENDAM evolved into HExDAM when the blast pressure profiles and structure vulnerability data were modified to accommodate conventional high explosives. The overpressure and impulse fields in HExDAM are computed according to Glasstone [8].

To accommodate the need for modeling VCEs, VExDAM was developed. VExDAM uses Van den Berg's Multi-Energy Method [9] to generate 3D overpressure and impulse profiles for spherical vapor clouds. Multiple spherical vapor clouds are used to model more complex vapor cloud geometries, and the effects of these sub-clouds are combined to produce cumulative overpressure/impulse fields. Once the initial overpressure and impulse fields are calculated, both HExDAM and VExDAM use the same methodology to compute shielding effects and injury/damage.

The shielding algorithm in ExDAM uses the actual design of buildings to provide more detailed results. For example, a blast wave may destroy window glass and wood-frame walls in the model, allowing persons standing behind the window or wood-frame wall to receive the full effect of the blast, but leave a concrete wall intact, shielding people behind that wall. ExDAM models these effects, which allows evaluation of existing structures as well as possible mitigation measures such as blast hardening of structures and addition of protective berms or walls.

Damage effects are calculated based on the material type (e.g. glass versus wood-frame construction versus cinder block construction). Injuries are determined based on the ExDAM human body model, which is composed of 28 total body components and 19 different body component types (e.g. various bones, organs, etc.). The model accounts for the fact that different materials/body parts are sensitive to different aspects of a blast wave. For example, ear drums are sensitive to the peak overpressure value, while long bone injuries are caused more by dynamic pressure. Damage levels are typically reported in four categorized: no damage, slight damage (useable, requiring minor repairs), moderate damage (partially usable or temporarily unusable, requiring major repairs), and severe damage (permanently unusable, irreparable). Injury levels are typically reported in six categories: no injury, walking wounded, needs minor surgery, seriously injured requiring major surgery, unlikely to reach hospital alive, and deceased. ExDAM presents damage/injury levels in a straightforward color-coded visual format with associated numerical data in tables.

Automated Sub-Cloud Creation in ExDAM

In contrast to conventional methods, in which an explosion VCE is regarded as a single entity, in the Multi-Energy concept a VCE is rather defined as a number of sub-explosions corresponding to the various partially confined/obstructed areas in the cloud [10]. In this Multi-Energy concept, a turbulence generating environment is required for the development of an explosion from a premixed combustion. If the boundary conditions of the expanding flow field induced by a premixed combustion are such that turbulence is generated, and the flame, which is transported by convection in the flow field, will interact with the turbulence: the turbulence increases the flame front area (the interface between reactants and combustion products) by which the combustion process intensifies and more reactants are converted into combustion products. The stronger expansion results in a higher velocity and enhances turbulence, which triggers a positive feed-back coupling between turbulence and combustion.

The Multi-Energy concept states that a blast is generated in a VCE only in the parts of the vapor cloud which are congested and/or partially confined, and it is very difficult to detonate an unconfined vapor cloud from an accidental release of hydrocarbons in an open area. As such, for a flammable gas cloud, significant overpressure can only be generated in those parts of the cloud which have a substantial degree of partial confinement and/or are congested due to the presence of obstacles.

This congestion/confinement foundation of Multi-energy concept provides researchers [11] [12] a way to qualitatively estimate the initial explosion strength on a scale ranging from 1 to 10. ExDAM uses this concept to quickly and effectively build sub-clouds around pre-defined congestion zones: the size of sub-clouds will be limited by the size of congestion zones. The procedures are described below:

- Define congestion zones and prepare the congestion zone dimensions based on the configuration of the facility. See Figure 1;
- Import the congestion zones into ExDAM. See Figure 2;
- Select a source center for an accidental release, provide a dispersion radius, and ExDAM automatically creates sub-clouds bounded by each congestion zone. See Figure 3.

Figure 1. A Typical Industrial Facility.

Figure 2. Congestion Zone Assignment in ExDAM.

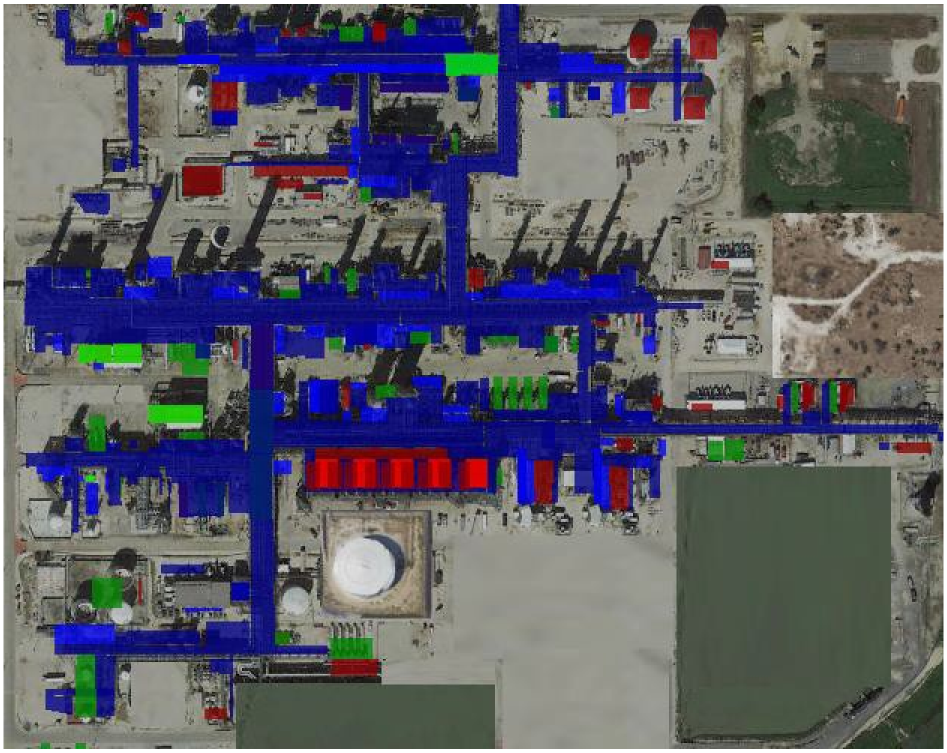
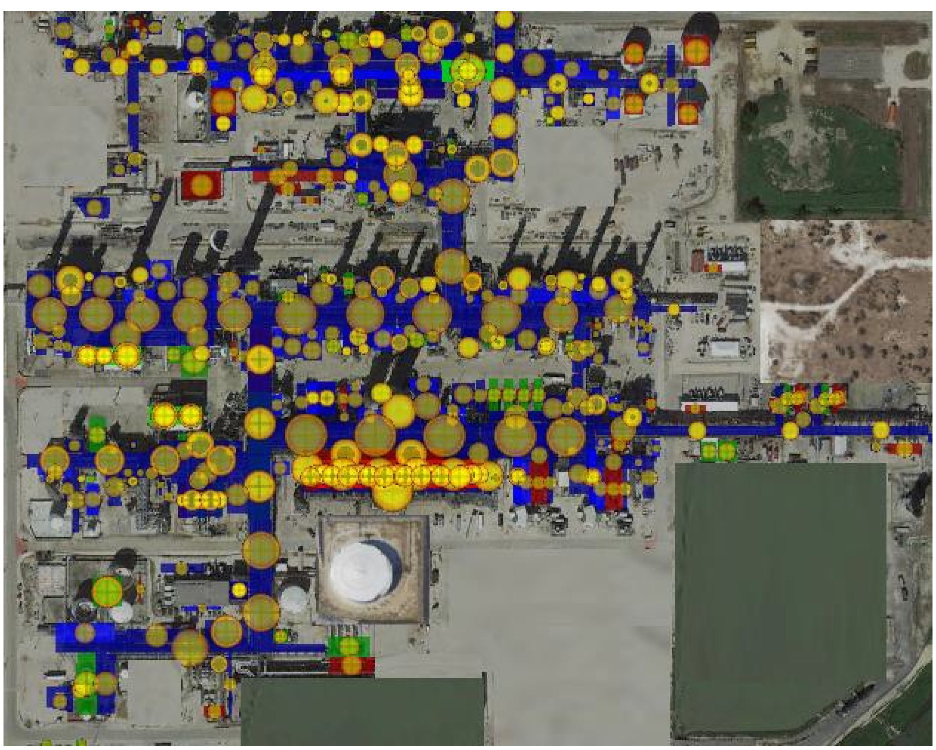


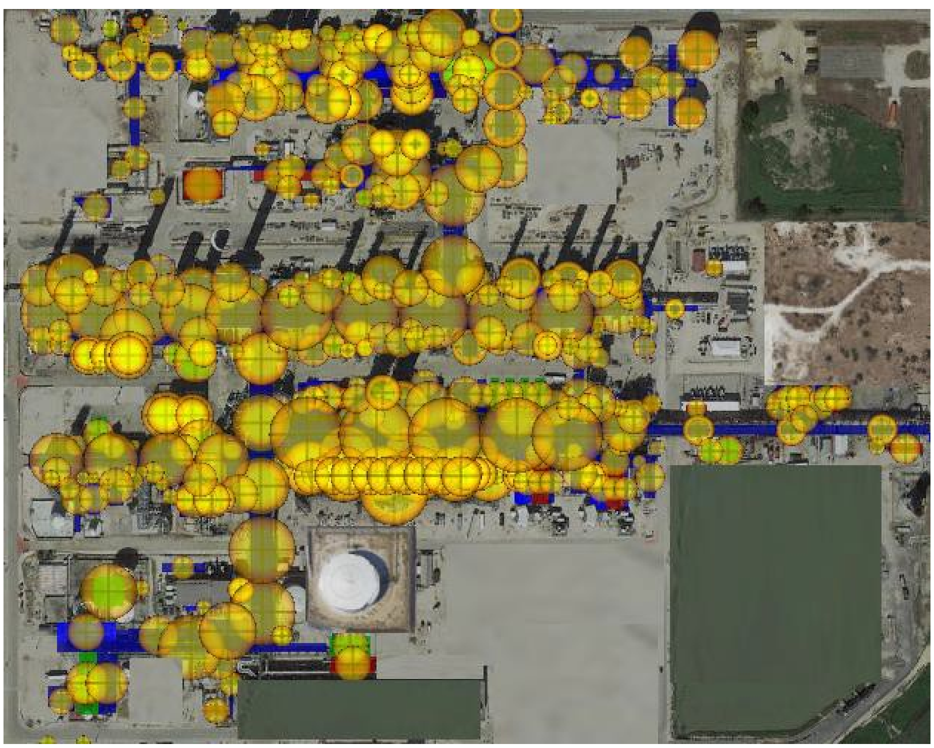
Figure 3. Sub-Clouds Bounded by Congestion Zone in ExDAM Assuming Dispersion Covers Entire Industrial Facility.



Experimental data indicate that gas explosions may develop overpressures which range from a few millibars under unobstructed or unconfined conditions, up to more than 10 bars for severely congested and confined conditions [13]. As such, when congested portions of the blast cloud are present, the blast produced by the remainder of the cloud (unconfined areas) is assumed to be "negligible". Figure 3 indicates that instead of creating one large vapor cloud based on the dispersion radius, ExDAM creates sub-clouds tailored to the size and location of the individual congestion zones within the dispersion radius.

The Multi-Energy concept is based on the assumption that detonation in the uncongested parts of a cloud can be ruled out. It is assumed that the uncongested fuel-air mixture is too non-homogeneously mixed to maintain a detonation. This assumption seems to be realistic for a wide range of conditions. Fuels of relatively high reactivity, however are more susceptible to denotation. In particular, in applications with more highly-reactive fuels such as ethylene or propylene, and/or situations where vapor cloud dispersion is suppressed and the fuel is mixed well with air and develops sufficient homogeneity, it may be realistic to consider the possibility of detonation in a substantial portion of the unconfined mixture. ExDAM takes this into consideration, and allows the involvement of the flammable gas outside of congestion. Figure 4 shows the sub-clouds with 60% increase in radius comparing with the sub-clouds in Figure 3.

Figure 4. Sub-Clouds with Involvement of Flammable Gas Outside of Congestion Zone



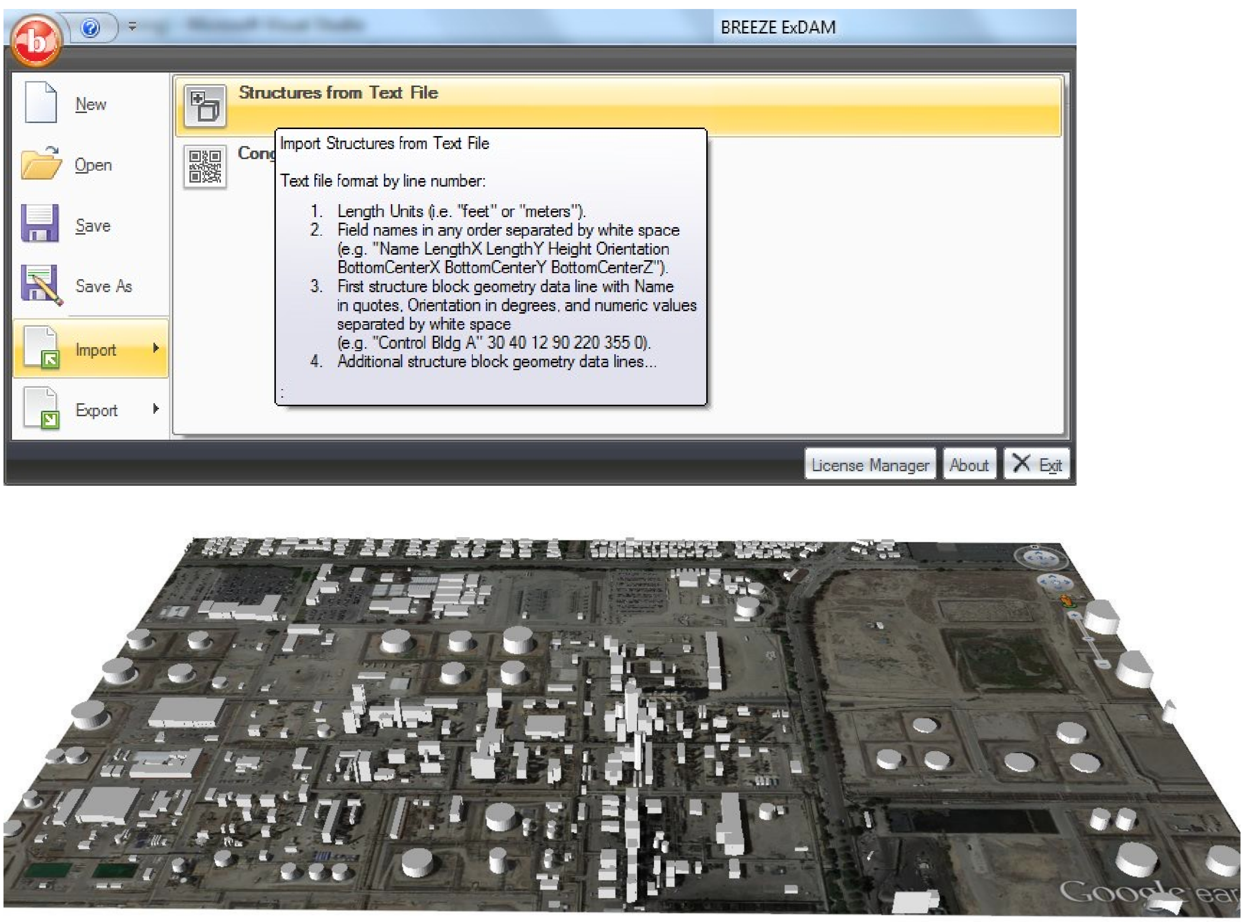
Large-Scale VCE Consequence Modeling with BREEZE ExDAM: A Demonstration

A demonstration of consequence modeling of a large-scale ethylene VCE with BREEZE ExDAM is presented in this section. The development of this large-scale VCE consequence modeling involves three steps:

☐ Edit Building Structure.

Complex building/block structures can be quickly created within ExDAM's 3D window using an extensive set of basic block editing operations (e.g. cut, stretch, copy, rotate, translate) and advanced shape editing functions (e.g. extrude/interpolate/extrapolate, cylinder/sphere, building with walls/floor/ceiling/windows/people). Structure editing in ExDAM is facilitated with options to import images and 2D/3D line/surface models (e.g. DXF or DWG format). ExDAM is further equipped with a tool to import massive building blocks from a text file with predefined coordinates and dimensions. Figure 5 shows the ExDAM UI for importing structures from text file and the populated building blocks on a 2D base map in ExDAM 3D window.

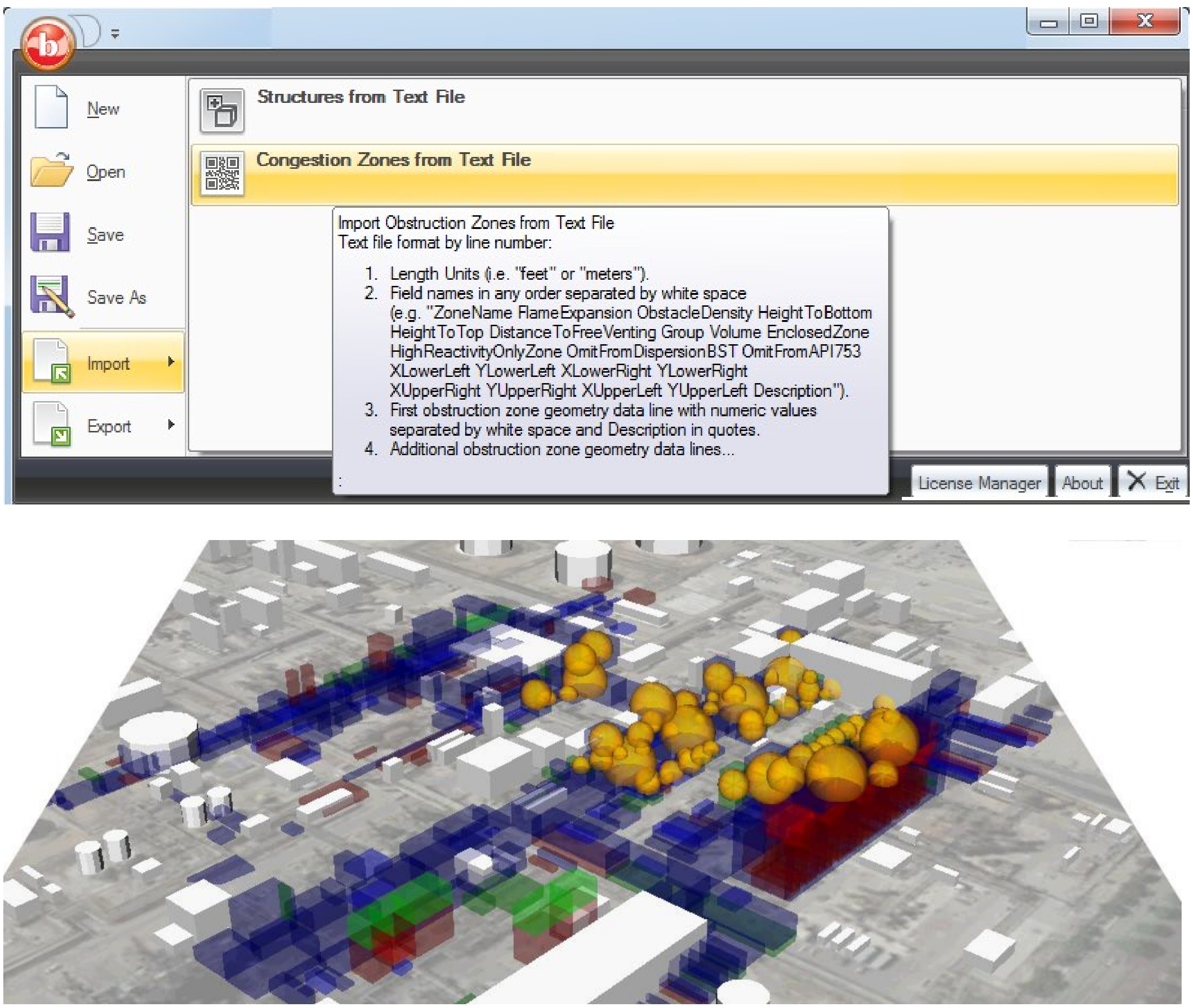
Figure 5. Importing Structures from Text File



☐ Create Vapor Clouds.

With the automated sub-cloud creation tool in ExDAM, hundreds of vapor clouds can be quickly created with a few mouse clicks and keyboard operations and precisely located around congestion zones. The size of each vapor cloud is determined by the size of corresponding congestion zone and the degree of user-specified involvement of flammable gas outside congestion zone, regardless of the actual quantity released during an accident. The number of vapor clouds will be determined by the distribution of congestion zones and the dispersion radius. Figure 6 shows the ExDAM UI for importing congestion zone and populating ethylene vapor clouds with a 100 meter dispersion radius of a release point.

Figure 6. Importing Congestion Zone from Text File and Automatic Creation of Vapor Clouds



☐ Specify Sample Grid.

A pressure/impulse sample grid is specified with a fixed boundary and fixed resolution in 3D. Peak pressure/impulse value will be computed for each sample grid point.

Figure 7 shows 2D overpressure contour plans above ground. The upper panel shows overpressure modeled without shielding effects; the lower panel is modeled with shielding effects. The computed overpressure at each grid point is the sum of overpressure from all sub-clouds at that point. Two critical levels of 0.6 psi and 0.9 psi are defined in API 753 for portable light wood trailers. The endpoint distances to both critical levels are shortened when buildings provide shielding behind.

Figure 7. Overpressure Contour Plans

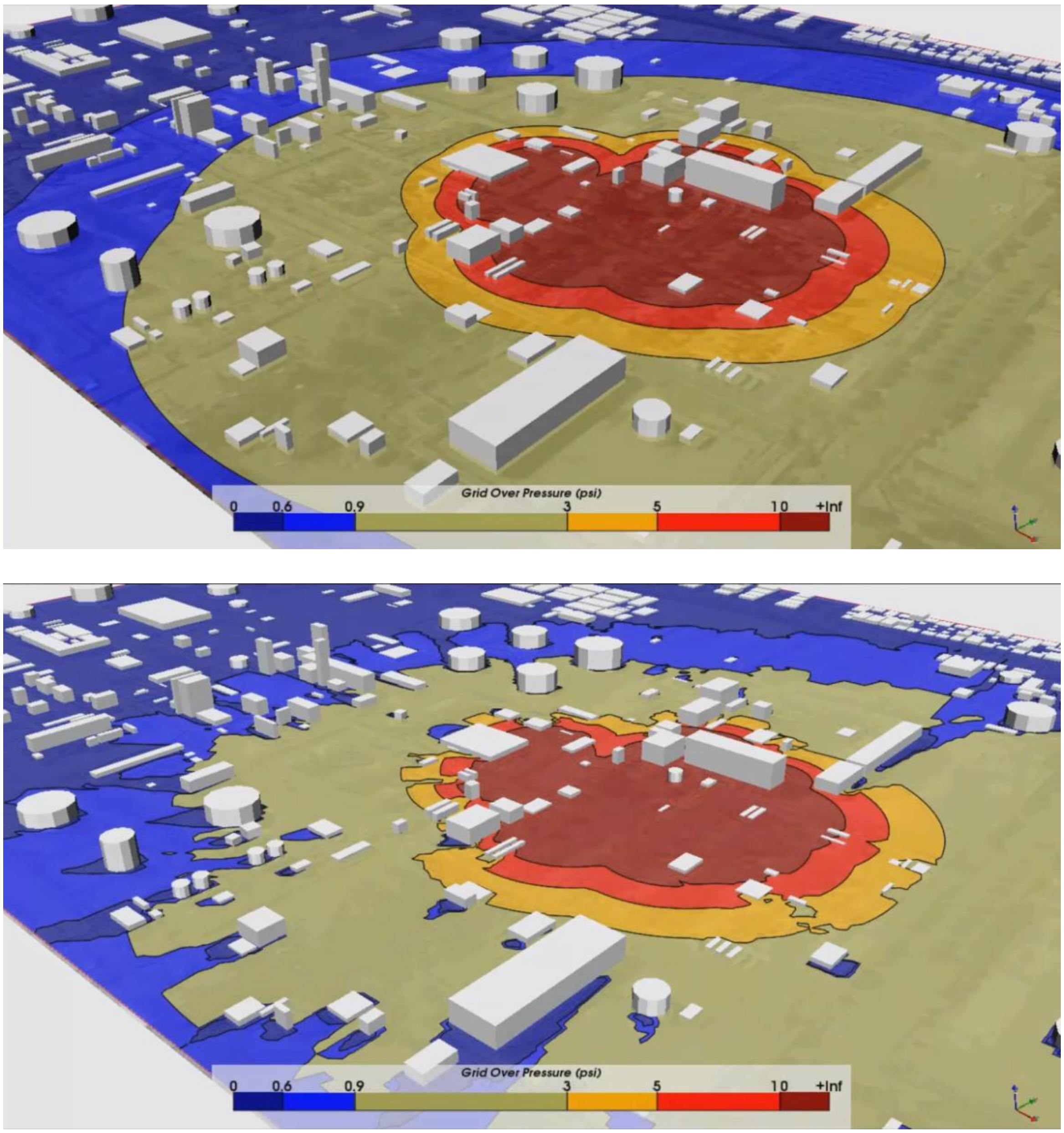
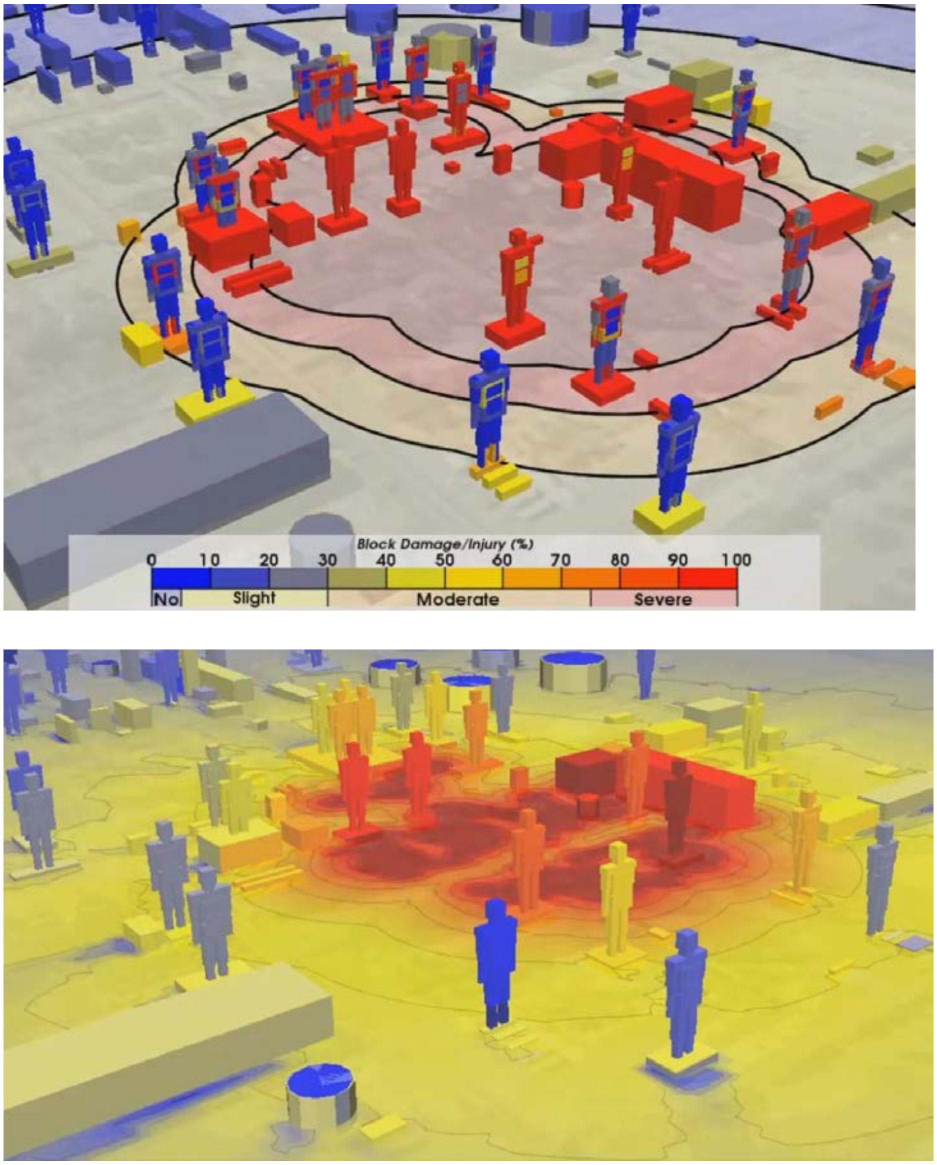


Figure 8 shows color-coded resulting damage levels to the buildings closest to the blast center and injury levels to the people closest to the blast. As before, the upper panel is modeled without shielding effects; lower panel is modeled with shielding effects. For a better view, the people are enlarged. Note how structures provide shielding to people inside and structure behind.

Figure 8. Color-Coded Damage/Injury



Summary

The BREEZE ExDAM model provides an intermediate complexity solution, comparing with basic phenomenological models and complex CFD models. ExDAM is well-suited to modeling explosions of vapor clouds in environments where large obstructed areas are presence and shielding caused by structures and people may have an effect.

The congested/confined area principle in the Multi-Energy concept is adopted in ExDAM. Hundreds of vapor clouds can be quickly and precisely developed around the congested boundary defined within a dispersion radius during an industrial accident release, so that large-scale ECM using ExDAM is made relatively simple to perform and understand in comparison to CFD modeling. Flammable gas outside congestion zone are generally ruled out from ECM. However, depending on the actual situation, an adjustment can be made using ExDAM, and portions of the uncongested flammable gas cloud can be involved in the ECM.

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