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Numerical Simulation of Blast Action on Civil Structures in Urban Environment

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Abstract. Nowadays, a lot of industrial accidents accompanied by explosions are happening throughout the world. Also, increase in the number of terrorist acts committed by means of explosions is observed. For improving safety of buildings and structures it is necessary to raise their resistance to explosive effects, as well as to be able to predict degree of potential damage upon explosive loads of various intensities. One of the principal goals in designing the structure resistant to explosive effects is to determine the dynamic response of structures to the impact of the blast wave. To this end, the transient pressure loads on the walls of the civil engineering structures are to be determined. The simulation of explosion is highly complicated, involving an explosion causing the shock wave propagation in air and then interaction with a structure. The engineering-level techniques permit one to estimate an explosive shock impact only for isolated buildings. The complexity of the building, the presence of nearby structures and the surrounding environment cannot be taken into account. Advanced computer aid engineering (CAE) software techniques combined with the latest methods of discrete three-dimensional city modelling permits one to simulate and analyse the effects of explosions in urban areas with a precision which previously was not possible. In the paper, the simulation results are presented of shock wave forming due to a spherical explosive charge and its propagation in the vicinity of geometrical configuration imitating an urban environment. The numerical simulation of a flow in the vicinity of prisms of different cross-sections and heights located on a flat plate was performed. The calculations are carried out in a three-dimensional non-viscous formulation using ANSYS software. On a basis of simulation results, a complex wave structures were analysed, and all the peculiarities of flows and pressure history records on building walls were described and explained. The possibility of a correct description of the non-stationary wave flow in the vicinity of the complex of obstacles is demonstrated. The results are compared with the experimental data on the pressure distribution in gauges located on the prism walls. The estimation of shock wave exposure intensity was performed to different objects.

1. Introduction

Protection of civil structures from the threat of terror explosions or industrial catastrophes accompanied by explosions is one of the most topical challenges in modern engineering. To increase the safety of buildings we need to increase their ability to endure actions of explosions. The first objective on this way is the prediction of the explosion power and the estimation of the parameters of the blast impact on the objects under investigation. On the basis of these data, the degree of potential damage to the buildings under such an impact could be estimated.

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There are numerous teams doing research on the development of methods that allow estimating the dynamic explosive actions on buildings. These methods form the basis of state norms and regulations in engineering and maintenance of buildings. As a rule, these methods are based on semi-empirical theories that can be applied to various types of emergency events [1-2].

However, the norms and regulations only allow estimating the parameters of shock-wave impacts on buildings in simple cases. Simplified methods cannot estimate a process involving a complex shock-wave flow that appears when several charges of explosive matter explode in the vicinity of several buildings. Developing universal engineering formulae capable of describing the event with a feasible degree of precision represents a highly challenging task due to its complexity and multiple parameters involved.

Improvement of computational algorithms and development of modern software complexes allow numerical modelling of shock wave and detonation propagation in the environment while taking into account their interaction with the ground surface, the objects on it, and the deformation and destruction of buildings. In a general case, calculating the sustainability of buildings under the action of shock-wave loads involve the solution of a coupled problem of modelling the unsteady external flow and the response of the construction to the dynamic pressure.

Various in-house and commercial software complexes for computer aided engineering (CAE) can be used for modelling these phenomena, such as ANSYS CFD, ANSYS AUTODYN, LS-DYNA and others. They enable solving a wide range of tasks in gas dynamics, solid mechanics and allow calculation of fluid structure interaction (FSI).

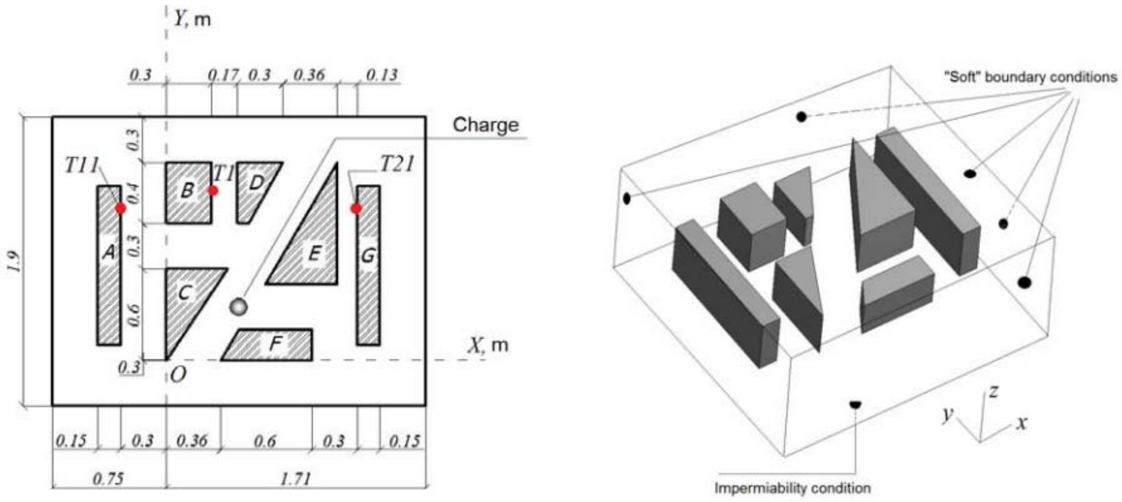
In previous papers [3-4], we developed the calculation technology for modelling shock-wave propagation and blast action on building structures which is based on the use of adequate mathematical models and modern software complexes. Shock-wave impact on isolated structure was modelled and ability of CAE instruments to proper determination of dynamic loads on the structure was demonstrated.

This paper presents the results of the calculation of shock wave propagation caused by a detonation of condensed explosive matter in the vicinity of a complex of prisms that imitates urban environment. We used the AUTODYN ANSYS module that is designed for modelling fast-occurring processes in an environment. The AUTODYN ANSYS allows to research a complex shock-wave flow structure formed as a result of the reflection of the initial shock wave from the surface and walls, the diffraction of the shock wave at the elements of the built-in area and the interference of multiple shock waves.

2. Problem setup

The plane view of the calculation domain is shown in figure 1, *a*. Seven buildings A - F of different cross-section and height are placed on the plate ground surface and imitate a cityscape. The maximal height of prisms (A and G) amounts $H_{max} = 0.45$ m and the minimal height of prisms is $H_{min} = 0.3$ (for prisms D and F). The distance between neighbouring objects is less or comparable with the size of objects in the transverse direction that characterizes this configuration as a densely built-up area. These simulations cannot be carried out in a symmetrical approach and require full 3D consideration.

The TNT charge of 16.0 g capacity is detonated at the point with coordinates (0.478; 0.35; 0.04 m). The problem statement was chosen in accordance of experimental data [5]. The static pressure behaviour was recorded in several gauges placed at the prism walls. Locations of the pressure measurement points are shown in figure 1, *a* and coordinates of the measurement points are listed in Table 1.



a) *b*)

Figure 1. Plane (*a*) and isometric (*b*) views of the geometry model

Table 1. Coordinates of pressure measurement points.

	x, m	y, m	z, m
T1	0.3	1.1	0.105
T11	–0.3	1.0	0.075
T21	1.26	1.0	0.075

3. Mathematical Model: Governing Equations and Boundary Conditions

The air region and the explosive charge were modelled on the basis of a hydrodynamic multi-material approach. Blast wave formation and propagation was computed with AUTODYN software designed to simulate high-speed processes of continuum mechanics.

All computations were performed for conditions of non-viscous flow. The 3D Euler equations were used for computations complemented with the ideal gas equation of state for air and the Jones-Wilkins-Lee equation of state (JWL) [6] for TNT:

$$\rho = A\left(1-\frac{\lambda\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1-\frac{\lambda\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + \lambda\rho e \qquad (1)$$

The values of the empirical constants A, B, R_1, R_2, λ are shown in Table 2, e is the specific internal energy and $\eta = \rho/\rho_0$ is the relative specific density.

Table 2. Empirical constants of equation (1).

Constant name	A, kPa	B, kPa	R_1	R_2	λ	e, kJ /m^3	ρ_0, kg/m^3
Value	$3.737\cdot10^8$	$3.747\cdot10^6$	4.15	0.9	0.35	$6.0\cdot10^6$	1630

All walls of the prisms and the ground surface are supposed to be non-deformable and usual impermeability boundary conditions are used. At the external boundaries chosen far enough from the region of interest, so called “soft” boundary conditions providing the outflow of perturbations through the boundaries were chosen.

The computational domains are a volume of air with the initial parameters corresponding to normal atmospheric conditions, namely, density ρ = 1.225 kg/m^3, temperature T = 298.15 K, static pressure P = 101325 Pa, the heat capacity C_p = 1004 J/kg·K.

The solver based on the finite difference method of high order of accuracy is used, that allows to effectively resolve high gradients and discontinuities of the flow.

The second-order Godunov [7, 8] and FCT [9] finite-difference schemes were applied for space approximation of the governing equations. For the temporal approximation, the explicit scheme of the second order was used in compliance with the stability conditions.

As the initial process of detonation in the open space was well described in the assumption of axial symmetry, to the moment when the primary shock wave reached the plate or some prism surface, it was carried out in a 2D approximation. Then the data obtained in the 2D calculations were interpolated to a 3D computational domain and the simulations were continuing taking into account the shock wave interaction with the substrate and prism surfaces.

4. Results and Discussions

Let's consider the shock-wave structure in the vicinity of the cityscape obtained using instantaneous static pressure contours in a horizontal plane-section z = 0.105 m at various time moments (figure 2, *a – f*) and computed pressure history (figure 3) in T1, T11 and T21 gauges.

Spherical shock wave (1) formed as a result of TNT detonation is propagating in an open space. It reaches the corner of the prism F at time t=0.1 ms and reflect from the wall of the prism F. After reflection, the shock wave intensity is about 6 MPa. At a certain moment of time, the shock (1) falls on the wall of the building C and corner of the building E and reflects by irregular manner forming the triple points denoted by 3, 4 and 5 in Figure 2, *b*. The shock wave (2) arises after reflection of the shock wave (1) from the building C and propagates toward the charge epicentre.

The interaction of the shock (6) reflected from the walls of the prism F (figure 2, *c*) and the shock (2) results in formation of the shock (7) at time $t \approx 0.4$ ms (figure 2, *d*). At the same time the shock (2) goes around a sharp corner of the prism C (figure 2, *c*, *d*) and interacts with the shock (1). At time t=0.4 ms the shocks (3) and (4) interact with each other in the channel formed between the prisms E and F. The shock wave (5) propagates from the charge epicentre and moves around the prism F (figure 2, *d*). In Figures 2, *e* one can see how the joint front of the shocks (1) and (2) comes through the channel between prisms B and D. It leads to the formation of several weak reflected shocks propagating to the charge epicentre. The interaction of the shocks (3) and (4) results in formation of the shock (8) which goes to the wall of the prism G. After reflection from the prism C the shock wave (2) interacts with the shock (5).

At time t=0.9 ms the shock-wave structure (1, 2) falls on the point T1 located at the wall of the prism B. The shock (8) falls on the wall of the prism G and reflects by irregular manner (figure 2, *f*). The shock (8) repeatedly reflects on walls of the prisms E and G that leads to several peaks of static pressure in T21 located at the wall of the prism G (figure 3, *e*). After the shock (8) a rarefaction zone with low values of pressure (≈ 43 kPa) is formed. There are several pressure peaks in T1 (figure 3, *a*) caused by the arrival of weak secondary shock waves forming due to the interaction between secondary shock waves and weak shock waves reflected from the walls of prisms B and D.

Further wave structure analysis is complicated by a large number of shocks and rarefaction waves formed in result of numerous interferences, reflections and diffraction of the waves. This flow features lead to occurrence of local pressure peaks at the walls of prisms and forming local rarefaction zones behind fronts of shock waves.

At the second step the comparison of simulation results and experimental data [5] on static pressure history (figure 3, *a*, *c*, *e*) and on effective momentum history (figure 3, *b*, *d*, *f*) in T1, T11 and T21 gauges located on the walls of objects B, A and G was performed. In figure 3, the symbols stand for experimental data [5] and the lines show the pressure and effective momentum history computed with Godunov (1) and FCT (2) schemes. The picture shows that both schemes predict the pressure loads on the building walls including positive and negative phases. The FCT scheme is better in predicting the peak amplitudes and secondary waves.

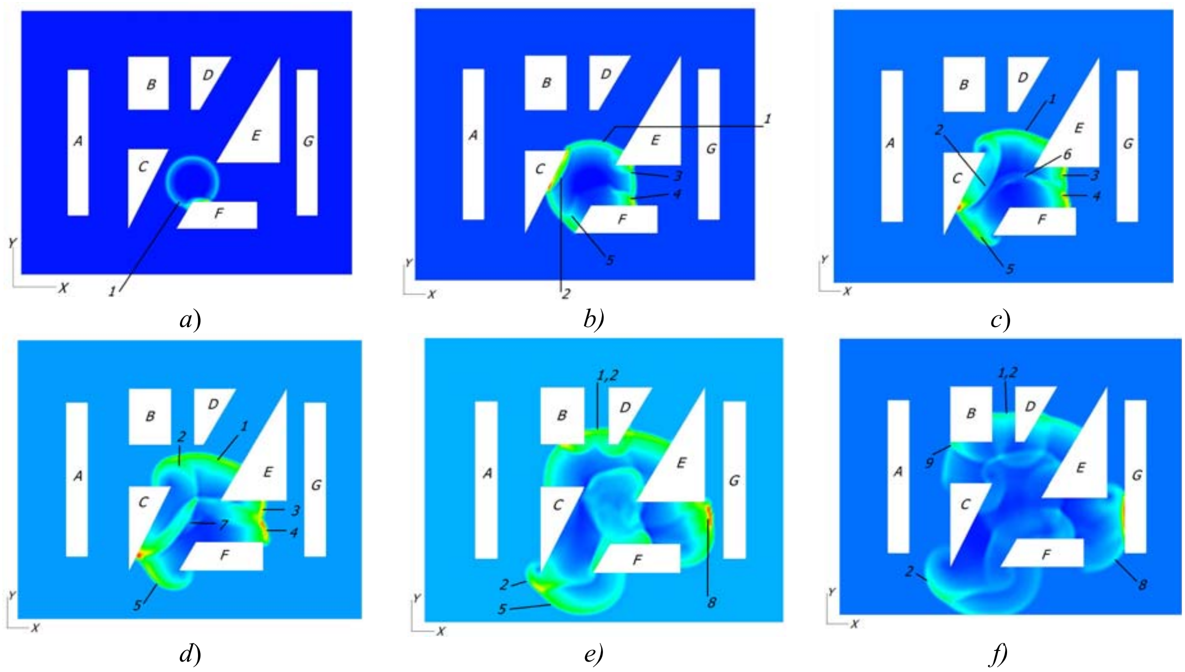


Figure 2. Instantaneous pressure fields at various time moments: 0.1 (*a*), 0.2 (*b*); 0.3 (*c*); 0.4 (*d*);0.7 (*e*); 0.9 (*f*)

As figure 3*a* shows, the first maximum pressure peak in T1 is P_{max}= 200 kPa in computations with Godunov scheme and it is P_{max}= 260 kPa for the case when FCT [9] was used. The maximal value of first pressure peak in T1 obtained from experimental data is about 300 kPa.

Rarefaction phases obtained for T1 and T21 are long-term (≈ 1.5 ms for T1 and ≈ 1.7 ms for T21).

The amplitude of pressure changes for the negative phase is significant in T21 (≈ 60 kPa) and comparable to peak values of pressure load on the wall (≈ 80 kPa) that occur due to the arrival of SW8 on the wall of the building G. The presence of a rarefaction phase with significantly lower pressures relative to the ambient pressure is unfavourable for buildings and can lead to window and door ejection, destruction of roofs and piles in some cases.

In order to describe the dynamic impact of a shock wave on a building it is also important to estimate the values of the shock wave effective momentum. The impulse loads acting on the walls of prisms at the consideration points are shown in figure 3, *b*, *d*, *f*. Time periods of effective loads on the walls of prisms A, B and G include several characteristic phases like phase of compression and rarefaction of wave impacted on the walls.

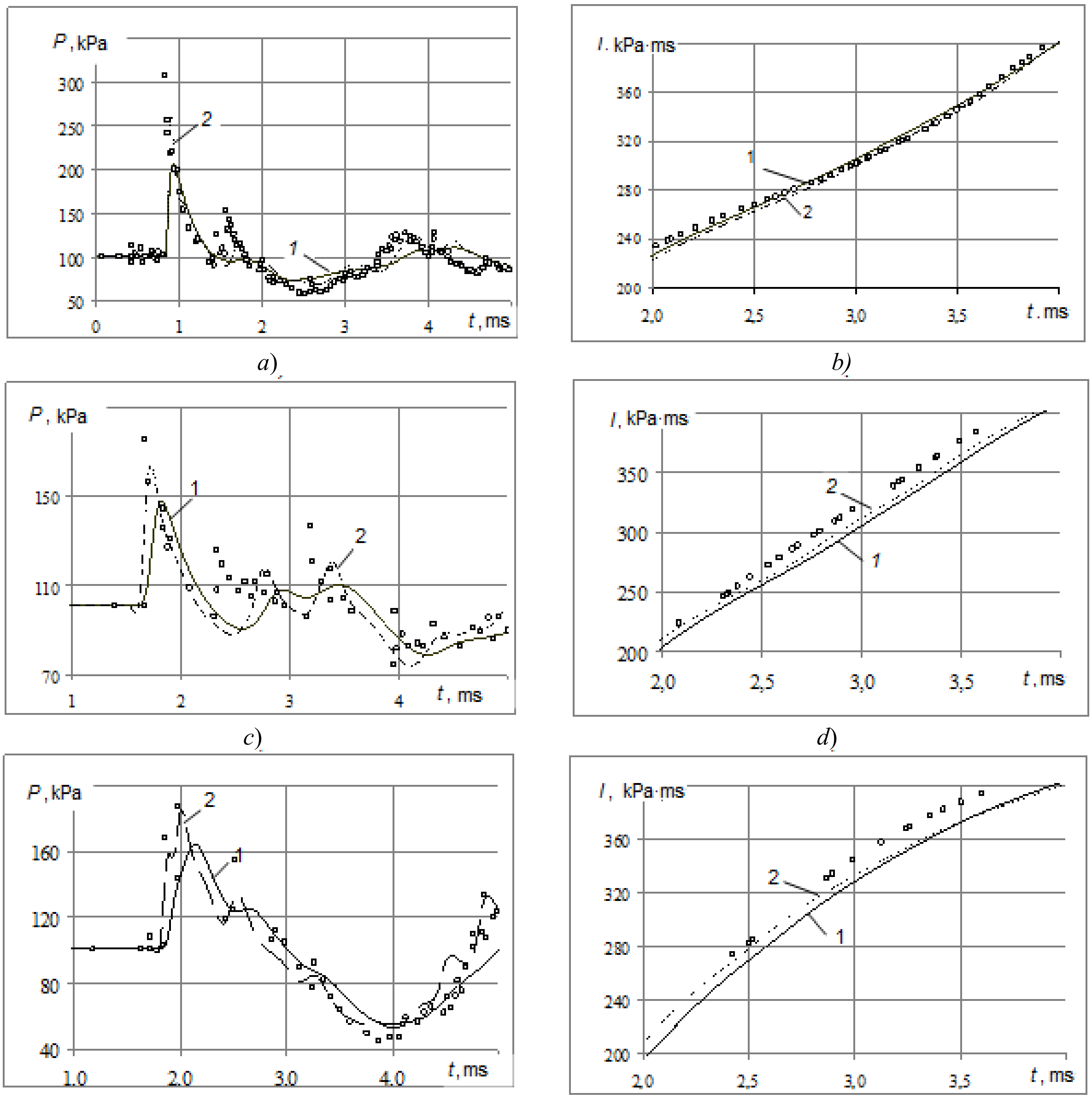
Thus, the presented results of the calculations make it possible to analyse in detail the complex wave structure of the flow formed after detonation process of the condensed explosive charge. The comparison of the calculation results with the experimental data [5] has shown a satisfactory agreement. This allows us to talk about the possibility of using the described methods of mathematical modelling to predict shock-wave loads on the walls of buildings and structures located in densely build-up urban environment.

Figure 4 presents the pressure-impulse (P-I) diagram which is showing the range of the critical values of excess pressure $P - P_0$ and blast wave momentum:

$$I(t) = \int_0^t P(\tau)\, d\tau \qquad (2)$$

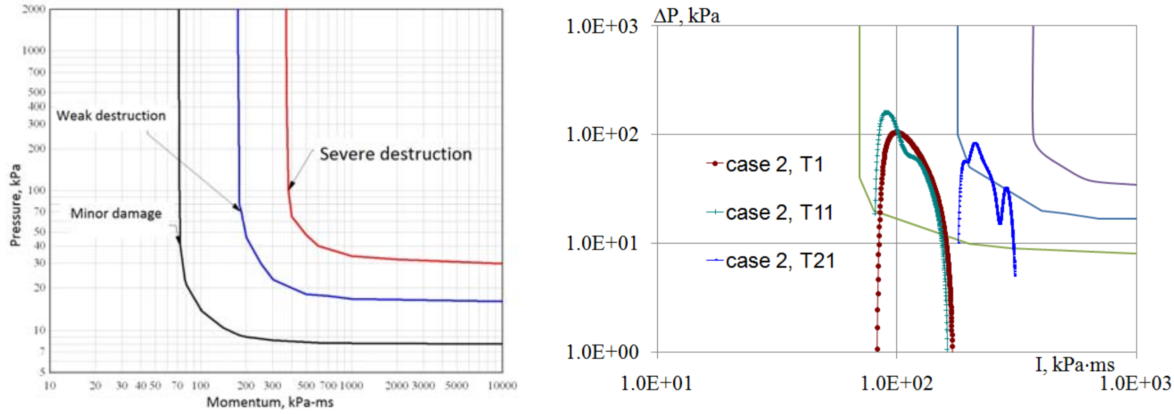
where P_0 – the ambient pressure.

Juxtaposition of simulation results with P-I diagram (figure 4, *b*) has shown the iso-response curve plotted for the measurement point T21 covers the area corresponding minor and weak destructions of objects. The iso-response curves plotted for the measurement points T1 and T11 covers only the area corresponding minor destructions.



f)

Figure 3. Computed (lines, 1 - Godunov scheme, 2 - FCT) and experimental (symbols) pressure history (*a*, *c*, *d*) and effective momentum history (*b*, *d*, *f*) in T1 (*a*, *b*), T11 (*c*, *d*) and T21 (*e*, *f*) gauges



a) *b)*

Figure 4. Pressure-impulse (P-I) diagram for a general structure type and load type (*a*); Juxtaposition of simulation results with P-I diagram for several gauges on the walls of objects (*b*)

5. Conclusions

- The test case of explosive charge detonation and blast wave propagation in the vicinity of generic cityscape of several prismatic bodies installed on a flat plate was investigated numerically using ANSYS AUTODYN software;
- On a basis of simulation results a complex wave structure was analysed, and all the peculiarities of flow and pressure history records on walls of objects were described and explained. The results indicate the necessity to take all the surrounding buildings into account when computing the blast loads on buildings in an urban environment;
- The comparison of two numerical scheme abilities has shown the better FCT properties to predict fine flow details;
- Juxtaposition of simulation results with experimental data available were performed and a satisfactory agreement on the static pressure behaviour in several gauges was obtained;
- Juxtaposition of simulation results with P-I diagram (figure 4, b) allowed us to determine the areas of possible destruction of objects. It is practically useful in the design of buildings and structures.

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