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Explosion hazard to buildings and design load parameters

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Abstract

The paper deals with the effect of explosions on building structures. The term hazard is defined as a source of danger. The sources of these effects may include blasting operations in a quarry, a dust explosion close to a pipeline or reservoir crack in a chemical plant or oil refinery, a collision of cistern vehicles in road or rail transport, a terrorist attack or an explosion of explosive or inflammable gas or dust clouds in the vicinity of the assessed structure. The risk of these explosions is explained by the examination of a nuclear reactor structure. First, information on the potential sources of danger is collected from the area from a diameter 10 km [1] area around the assessed structure and the maximum quantities of explosive materials are determined. Then the design load parameters for the concrete nuclear plant are given, related to the quantities and kinds of explosives. The dominant explosion effect on a building structure is defined as the history of (a) propagating loading air pressure wave of maximum intensity caused by dust clouds or (b) seismic effect produced by ground vibrations. The results of the analysis are simplified criteria for the failure of the assess structure and the permissible limit response characteristics determined by a 3D analysis of the structure.

1 Loading of the structure by explosion effects

The sources of shocks affecting the threatened building during explosions of the most varied type, location and geometry of charges may include the following events: (a) blasting operations in the given area; (b) catastrophic explosions of

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media in pipelines, tanks and storage reservoirs of combustibles and explosives; (c) catastrophic explosions of mobile train, truck and/or boat tanks and cisterns; (d) explosions of gaseous clouds of explosive and combustible mixtures; (e) terrorist attacks.

If we assess the potential sources according to the mechanism of shock origin, the blasting operations and terrorist attacks using explosives will cause directly rock mass vibrations like an earthquake of natural origin, but of different frequency and intensity parameters. The air pressure wave in the case sub (a) is negligible. For the cases sub (b) through (e), which may bring about the failure of the structure, the rock mass vibrations are of secondary significance. In the case of gaseous or dust mixtures with the air the explosive medium must appear (leak) first; then the gas or dust mixture must blend with the air and finally the explosion of this mix must be initiated.

The mix explosion may take place also in the case of the leakage of an already burning medium from a pipeline or a storage tank, which will turn into a detonation. The explosions of detonating mixes generate, apart from an air impact wave, also seismic effects in geological environment. The air pressure wave generated by an explosion of the mix, analogously with the air pressure wave generated by a terrorist charge (e) placed on or below ground level, has significant destructive effects. A gaseous cloud (d) of a combustible and air mix, moreover, is dangerous, because it can infiltrate the buildings through window and door openings where upon its explosion may be initiated. In such a case the pressure wave is significantly more destructive, as the explosion takes place in a closed or quasi-closed space. As the parameters of the pressure wave and of the seismic effects are the products of the same action, let us combine the analysis of these phenomena in the same paragraphs concerned with the individual potential explosion sources.

The assessment of the hazard to buildings resulting from the effect of explosion due to the leakage of combustibles (fluids, gases and vapours) from oil refineries, storage tanks, pipeline systems (both above and below ground level), tanks and cisterns must be based, according to [6], on an assessment of the danger generated by potential explosion sources situated within a diameter 10 km [1] area around the threatened structure. In the sections to follow we shall compare the hazard rate of a building situated in the Central Bohemian basin by explosions of the most varied type incl. the determination of the load level for which this structure must be assessed.

Blasting operations

At a distance of only 1 950 m from the building there is a quarry. The measurements of seismic effects of a bench blasting operation in this quarry with a total charge of 2 143.8 kg (maximum charge for one time phase 100 kg, timing DeM SICA 1 - 11 and the corresponding effective charge weight of 454 kg) were made in the foundations of the examined building at a distance of 1 950 m from the blast epicentre. The measured frequency spectrum of vibration

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velocity is shown in Figure 1 (horizontal direction A is longitudinally parallel with the line connecting the building and the quarry).

The measured velocity level shown in Figure 1 is considerably low and corresponds with bench blasts in standard use. These measurements, together with other archive records, were used for the derivation of empirical environment equations for the seismic signal propagation in the given area:

$$v = k \cdot \sqrt{m_{\mathrm{ef}} / l} \tag{1}$$

$$k = 946.5 - 114.712 \cdot \ln(l) \tag{2}$$

where k is transfer function for the given area; l is distance [m] from explosion epicentre to the assessed building; m_{ef} is effective magnitude (mass) of the blasted charge [kg]; v is vibration velocity [mm/s]. Note to the formula: if we substitute in this formula for the distance of the assessed building from the bench blast epicentre l = 1 950 m and effective charge mass m_{ef} = 454 kg, we obtain the vibration velocity v = 0.847 mm/s. This vibration velocity, determined on the basis of this empirically derived formula, does not contain the influence of the frequency of the seismic signal propagating from the source. A comparison of Figure 1 with this computed velocity reveals the approximate character (insufficiency) of the formula. On the other hand, with regard to the possible variability of geological environment and the possibility of its characterisation with a single coefficient k the computed velocity represents a very good approach to the measured reality (Figure 1). The coefficient of safety (reliability) of this formula can be estimated approximately at 2, so that the measured values may be even twice as large as those computed by the formula. The computed amplitude of vibration velocity corresponds with the low-frequency load region, i.e. approximately the frequency of about 1.5 Hz.

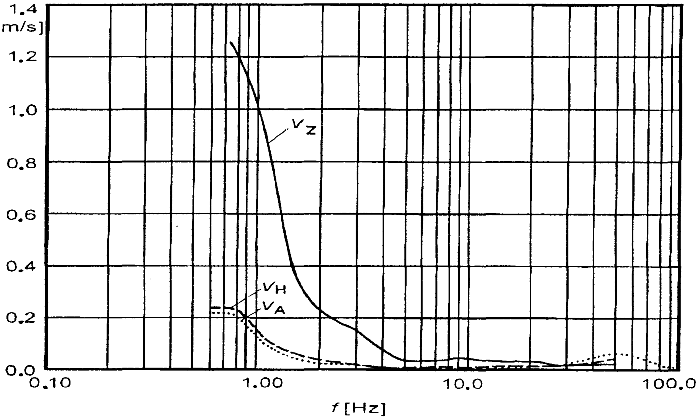

Figure 1: Measured velocities v in vertical (z), perpendicular (h) and axial (a) directions versus frequency f of seismic load

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2 Intensities of catastrophic explosions

Pipeline systems with combustible fluids

The building structure may be threatened by a pipeline filled with a combustible or explosive medium. Such pipelines are used as long distance product pipelines or distribution pipelines in industrial plants. At a distance of some 3.5 km from the assessed building there is a long-distance crude oil pipeline and a product pipeline. The oil pipeline of a diameter $d = 500$ mm has a maximum flow rate of 1 400 m^3/h, the diameter 200 mm product pipeline conveys BA (petrol) and NM (diesel oil) at the flow rate of 150 m^3/h.

Let us assume a pipeline failure and a leakage of the conveyed medium. In the case of a substantial damage to the pipeline, the pressure of the conveyed medium will drop and the pumping plant operators can notice a substantial leakage within a period of the order of 10 min. Let us estimate the quantity of escaped medium at the 10 min. flow through the failed pipeline:

oil pipe line: $1\,400 \times 0.17 = 233$ m^3/h, i.e. $233 \times 0.850 = 198$ t

petrol pipeline: $150 \times 0.17 = 26$ m^3/h, i.e. $26 \times 0.800 = 21$ t

These quantities will penetrate first into the ambient soil or will start spouting above ground level (being under pressure). Obviously they will start burning and evaporating into the atmosphere and forming a gaseous cloud of the mix of petroleum or petrol vapours with the air. Until that moment the assessed building, situated at a distance of 3.5 km from this potential source of explosion, will not be in danger. The gaseous cloud, which will form on the site of pipeline failure, will not contain the whole quantity of escaped medium, but only its part. In the case of petrol leakage the evaporation will be faster than in the case of crude oil. According to the analysis of the data [2] of petrochemical companies on similar failures on the world scale the failure of a crude oil or products pipeline will generate a gaseous cloud containing a blend of carbohydrates (such as petrol) with air containing approx. 25 to 30 t of petrol, the TNT equivalent of which is 1.03 t TNT. That means that it is realistic to assume approx. 1 t TNT for the petrol could and approx. 4 t TNT for the oil cloud. The explosion of this cloud may be initiated on the site of its origin or it may be carried by the wind to the proximity of the assessed building.

Storage reservoirs of combustibles in oil refineries and similar plants

The potential danger of explosion may consist in direct leakage of the media from oil refineries, storage reservoirs of petroleum products, semi-products and liquefied gases. Most dangerous are liquefied gases on the basis of light carbohydrates (propane, propane-butane and butadiene) with flash point below 21°C. These liquefied gases are usually stored at –4°C. In case of failure of aboveground reservoirs they evaporate fast and form a gaseous cloud. As a rule, the firms are not protected against terrorist attacks, as a result of which the failure of a liquefied gas reservoir may be caused also by a shot from a car

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passing the works along a public road. However, the failure of a liquefied gas reservoir can be due also to its wear, corrosion or human factor (negligence of operator). According to the data of the chemical works in the proximity of the assessed building the area of the factory has liquefied gas reservoirs storing max. 10 340 t of liquefied gas, mostly butadiene; average content of all storage reservoirs is 1 550 t. According to the company information one reservoir can take 1 000 m^3 of gas which means, given the 0.6 t/m^3 weight of liquefied gas, some $1000 \times 0.6 = 600$ t of gas. These storage reservoirs are situated at a straight-line distance of 9 km from the assessed building. As the stored gases are heavier than air, the cloud of these carbohydrates may be carried by wind to the building. Although the converted quantities of these gases are relatively large, the world statistics of failures in chemical industry show that the magnitude of the cloud of these gases usually varies between 20 t and 60 t TNT. For instance, the Flixborough explosion – 18 t TNT, Port Hudson – 35 t TNT; major explosions – 100 t to 125 t TNT – are obviously loaded by a considerable uncertainty of estimate.

Whether we consider the upper limit of 60 t TNT or 100 t TNT, it corresponds merely with 5.5 t and 9 t of carbohydrates respectively entering the explosive reaction. These values are relatively very low in comparison with the quantities of stored gases and are even smaller than the quantities transported in one truck or railway cistern. The maximum limit of potential danger of leakage and explosion of stored gases is determined by the possibilities of escape from storage reservoirs and their evaporation and blending with the air rather than by their maximum quantity stored in the reservoirs. Consequently the assessment of the danger for the nearby building structures due to the liquefied gas storage reservoirs must consider the threat to the structure in two variants:

a) explosion of one gas reservoir directly in the close proximity of the reservoir (full reservoir, containing in this particular case 600 t of gas, corresponds approximately with 600 × 0.2 = 120 t TNT),

b) gaseous cloud generated only by a part of the gas in the reservoir containing – according to world experience – up to approx. 60 t TNT of the mix of light carbohydrates with the air, carried by wind to the assessed building or to its close proximity.

Failures of road or railway cisterns

A truck cistern contains about 5 t of petrol transported by a heavy truck with a trailer; a railway cistern transports the quantity of a higher order. The hazards of road and rail transport, however, consist primarily in the fact that relatively small quantities are transported in a number of vessels and that the road or railway pass in the close proximity of threatened buildings, as a rule. In the case of failure the principal role is played by the speed of evaporation of these combustibles. For instance, during the railway accident in Illinois in 1974 the transported isobutane generated a cloud sized 800 × 1 200 m. Explosion was

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initiated after 8 – 10 min. and TNT its equivalent was estimated at 200 t to 400 t TNT.

The detonation conversion ratio for small quantities dispersed in a number of vessels is 200 kg TNT per 1 tonne of carbohydrates of calorific value of 42 000 kJ/kg. The danger of detonation is not very probable, if the escaped quantity of gases (carbohydrates) and vapours (petrol, crude oil) is smaller than 2 – 5 tonnes, the lower limit applying to light carbohydrates, the upper to the vapours of petrol, crude oil, etc. Consequently, in the case of escaped quantities of over 50 t of gases and vapours this quantity above 50 t corresponds only with about 10 t TNT. In the case of excessive quantities of escaped carbohydrates the blending of the combustibles with air is more difficult and the zone of concentration capable of detonation is more difficult to form. In the areas, where the ground forms a valley traversed by a road or railway, a railway accident is explicitly more dangerous. For this reason it is recommended to consider the following danger parameters, when assessing the threatened buildings, especially those located in valleys traversed by a railway transporting cistern trains with combustible carbohydrates: (a) explosion of 200 t TNT on the railway line, (b) penetration of a gaseous cloud of carbohydrates of 60 t TNT equivalent to the threatened building and its explosion.

3 Load generated by an explosion of a cloud of combustible gases and vapours

In the case of escape of combustible gases and vapours from storage tanks, cisterns, pipelines, etc. there are three variants of cloud behaviour: (1) the cloud merely disperses, because its quantity is insufficient or its explosion has not been initiated (the lack of initiation is highly improbable and unique); (2) the cloud burns freely and does not generate any pressure wave; (3) the cloud starts burning and this fire changes into a detonation generating a destructive air wave. The danger of change (conversion) of the burning process into a detonation originates only after 2 – 5 t of gases or vapours have escaped into the atmosphere except for hydrogen and its blend with combustible gases (CO, CH_4, etc.) for which the conversion of burning into detonation can start already if their quantity has exceeded 100 kg of the mix. The explosion will take place, if the velocity of flame propagation exceeds the sound velocity, or if the flame surface is very large. The conversion of burning into detonation attains the values of 0 – 10% by weight (in the USA 25 % are recommended) of the escaped quantity. This means that only a relatively small part of the burning cloud can detonate. The TNT equivalent of the detonating part of the cloud (for the quantities of escaped carbohydrate over 50) can be computed on the basis of the following approximate relation:

$$\begin{array}{ccccccc} \text{escaped quantity} & \times & \text{conversion coefficient} & \times & \text{conversion} & & \\ 1\ \text{t} & \times & 10 & \times & 2\% & = & 0.2\ \text{t TNT}. \end{array}$$

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For the treatment of the whole phenomenon and particularly for the sake of comparison of experimental and theoretically derived relations for building structures it is necessary to deal with the magnitude and the character of load (with particular reference to its history) and the assumptions valid for the distribution of this load over the surface of the structure. The explosion of a gaseous or solid explosive medium generates a pressure wave in the explosion epicentre. Its intensity and history are determined by the chemical characteristics of the explosive and its reactions with the ambient environment. Nevertheless, this fundamental characteristic depends primarily on the chemical reactions taking place during the explosion and, consequently, is relatively independent of the building structure (with the exception of the volume of interiors of building structures, if the explosion is assumed to take place in these interior spaces). From the explosion epicentre the pressure wave starts propagating in approximately spherical wave surfaces and reflects and modifies when hitting the surface of the building structure or the ground. The effect of pressure in the propagating wave, together with the pressure wave reflected from the surface of the building structure or the ground determine the magnitude of the load applied to the building structure and its history [3]. Particularly in closed rooms, industrial halls, etc., where multiple reflection of the pressure wave takes place, it is the size of this closed space that is decisive for the magnitude of the load applied to the structure. This effect of closed space for load formation is used e.g. in the relatively very small chambers of cartridge cases of firearms systems, in the closed chambers of bore holes and holes for the installation of charges in blasting operations or in impact pipes for the prolongation of the effect of the pressure wave overpressure, etc. There are numerous methods of various rate of approximation for the determination of explosion parameters (primarily the history of overpressure p_+ or underpressure p_-, the duration of overpressure or underpressure τ_+ and τ_- respectively, puls I_m, etc.). Nevertheless, more accurate determination is based on experimentally ascertained values, as a rule. The explosion generates a pressure wave the dominant effect of which on a standard building structure is manifested, as a rule, by the bending of its members [5], by their displacement along cracks of earlier origin or by their displacement resulting from the failure of joints, anchorages and fastening components of individual structural members, etc. It is permissible to base the description of loads on the following simplifying assumptions: (a) the loading pulse in time is approximately triangular, of the maximum intensity corresponding with the sum of the pressures in the incident wave p_{in} and the reflected wave p_{refl} on the surface of the loaded structure or a part thereof. If the load intensity is not known more accurately (e.g. from measurements), the resulting maximum overpressure load applied to the structure q_+ can be estimated from the overpressure of incident impact pressure wave $q_+ \approx p_{\mathrm{in}} + p_{\mathrm{refl}} \approx 2\, p_{\mathrm{m},+}$; (b) the pressure wave has a plane front (i.e. the load in the individual points of a plane structure acts without phase displacement) and acts in the direction of the normal to the middle plane of the loaded structure; (c) the load acts on the building structure (wall, floor, windows, etc.) continuously and is evenly distributed (it is not necessary to consider the local effect of concentrated loads for the standard dimensions of building structures or residential or industrial buildings); (d) in the linear computation of the effect of the underpressure and overpressure phases of the loading wave on the threatened structure it is possible to use the principle of superposition.

In the case of explosions of gaseous mixes (in contrast to the explosions of the charges of solid or fluid explosives), apart from the triangular phase also the underpressure phase is significant, the effects of which can be considered also as a triangular load, but with the opposite sign and phase displacement; both phases, the overpressure and the underpressure phase, can be considered separately, but in the way enabling the superposition of the results of both phases to determine their cumulative effect. If the impact wave hits an obstacle [3,4], such as a brick structure, it forms on the solid obstacle level a reflection overpressure p_{refl} which, together with the overpressure in the incident wave, loads the obstructing structure. It holds very approximately that $p_{\text{refl}} \approx p_{\text{in}}$ (compare the formula in par. (a) above for the simplification assumptions concerning the impact wave). In the case of explosion in a closed space of a room within the building structure, with relieving openings closed, the pressure in the incident and the reflected waves will increase by about 50% due to the reflections from the wall, floor and ceiling surfaces, so that the resulting overpressure load applied to the space defining structures can be expressed approximately by the formula $q_+ \approx 1.5\,(p_{\text{in}} + p_{\text{refl}}) \approx 3\,p_{\text{m},+}$. The overpressure duration is approximately double $\tau_{+,\text{tot}} \approx 2\,\tau_+$. Analogous formulas hold also for the underpressure phase. The history of the overpressure load phase has a very sharp overpressure peak and the pressure rise to the maximum of reflected overpressure is of the order of ms, as a rule. On the other hand, also the building structure is characterised by its inertial mass, the product of mass and acceleration. This inertial mass of the structure is displaced or rotated into its extreme (maximum) position which will manifest itself by the maximum deflection taking place approximately at the time t corresponding with a fraction of the respective natural period $T_{(i)}$ from the beginning of the load effect $t \approx T_{(i)}/4$. This natural period $T_{(i)}$, as a rule, corresponds with the lowest natural flexural vibration mode of the structure [4].

The estimate of explosion parameters due to solid charges or gas, vapour and dust mixes can be based on approximate relations valid for the estimate of the load field in the proximity of an obstacle, e.g. a brick wall of a building (derived for the explosion for the height of up to 20 m above ground level):

overpressure [MPa]: $$p_{\text{m}+} = 0.1\,m^{1/3} / R + 0.43\,m^{2/3} / R^2 + 1.4\,m / R^3 \qquad (3)$$

duration of overpressure phase [s]: $$\tau_+ = 1.7 \cdot 10^{-3}\,m^{1/6}\,R^{1/2} \qquad (4)$$

total pulse [MPa · s]: $$I_\text{m} = 6.3\,m^{1/3} / R \qquad (5)$$

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underpressure [MPa]: $p_{m-} = 0.03\, m^{1/3} / R$ (6)

durations of underpressure phase [s]: $\tau_{-} = 0.16\, m^{1/3}$ (7)

The quantities to substitute in these formulas are: the detonating mass quantity m [TNT equivalent in kg] and the distance from the explosion the R [m].

In the case of a charge explosion above ground level it is also possible to estimate the magnitude of the pressure wave in the soil in which the explosion effects infiltrate. (This motion is usually called induced wave in soils and rock). At a major distance from the explosion epicentre this induced wave manifests itself as technical seismicity excited by the explosion. The approximate formulas for the determination of the maximum overpressure $p_{m,soil}$ [MPa] of this induced wave generated by an air explosion at ground level, are:

$$p_{m,soil} = p_{m,air}\, [1 - 0.5\, h\, (1 - a_1^2 / a_0^2\,) / (a_1\, \tau_{+ \text{ or } -})] \qquad (8)$$

if $a_0 = (E_0/\rho)^{1/2}$ is the velocity of longitudinal wave propagation in the soil, $a_1 = (E_1/\rho)^{1/2}$ is the velocity of propagation of elastoplastic longitudinal waves in the soil. They are approximately the following velocities $a_0 = 200$ m/s and $a_1 = 100$ m/s for sands; 250 and 150 m/s for gravelsands; 300 and 150 m/s for sandy loams, etc., if E_0 is the modulus of elasticity of the soil under load relief, E_1 the modulus of elasticity of the soil corresponding with the elastoplastic state, ρ the bulk density of the soil, h the depth below ground level, τ and $p_{m,air}$ are characteristics of an air wave, R is distance from explosion epicentre.

Table 1. Approximate estimate of the rate of damage to the building as a whole with reference to defect description and impact wave overpressure $p_{m,+}$ on the site of impact wave interaction with the structure

Structural part	Defect description	$p_{m,+}$ [kPa]
Window glazing	Partly broken	1.5 – 2.0
Window glazing	Completely broken	3.5 – 7.0
Window, door and gate frames	Warped, torn out, fractured	12
Standard industrial buildings	Serious walls, roofs defects	17
R.C. or steel skeleton structures	Serious walls, roofs defects	53
Massive brick walls	Major cracks in masonry	70
Massive bricks and R.C.walls	Catastrophic destruction	100

4 Example of analysis of explosion effects

A detailed assessment of explosion effects on a building structure necessitates a dynamic analysis of the structure, based on the knowledge of the parameters of measured loads due to a concrete explosion in a concrete environmental configuration. A simplified assessment of the structure may be based on the criteria derived empirically, as a rule [2]. In terms of the TNT equivalent of

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5 Conclusions

The paper is concerned with the danger to building structures generated by explosions in their proximity incl. an estimate of loads affecting these building structures, generated by the explosion, as a basis for a dynamic analysis of the structure. The example of such assessment reveals that most dangerous for the buildings are the explosions of gases and vapours blended with air in the case of leakage from railway or truck cisterns, particularly in case of adequate ground configuration (deep valley). These cases are more dangerous than the explosions due to blasting operations in quarries, explosions in more distant petrochemical works or more distant oil and product pipelines.

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