Improving Safety Provisions of Structural Design of Containment Against External Explosion

Javed Iqbal
Pakistan Atomic Energy Commission

Saeed Ahmad
University of Engineering & Technology, Taxila, Pakistan

Abstract. Explosions may occur due to a variety of reasons that need to be identified and for which the probability of occurrence may need to be quantified. ACI Standard 359-07 "Code for Concrete Reactor Vessels and Containments" deals with the impulse loads as time dependent loads e.g. the dynamic effects of accidental pressure, the effects of pipe rupture reactions and Jet impingement loading etc. These impulse loads lie within the purview of internal explosions. However, the provisions to deal with the effects of external explosion against reactor containment are still in developmental stage. The present paper has, therefore, been directed to study the effect of external explosion on a typical Water Cooled Reactor (WCR) containment. A 1: 25 scale model of a typical nuclear power plant containment structure was constructed to determine the experimental relationships of airblast pressure time history as a function of surface explosion charge weight, distance to structure, structure height, as well as the simultaneous ground shock wave history. The similarity of soil parameters at the experimental site with the actual site conditions was ensured in order to determine the ground shock relationship. The success of the experimental programme was dependent on the ability to accurately measure reflected pressure and to collect acceleration data from wall-mounted accelerometers. The general practice is to utilize the air blast pressure values in the structural analysis and design against external explosion. The ground shock parameters are usually neglected during blast resistant analysis and design. In this paper, not only the airblast parameters have been studied but also the ground shock parameters have been dealt with. Therefore, the paper deals with the experimental determination of relationships of following airblast and ground shock parameters against scaled distance on containment scaled model.

1. INTRODUCTION

The importance of design of important structures against any terrorist or military attack has been under consideration quite and often in recent times. The paper deals with the scenario of surface explosion at various distances against a structure. A surface explosion generates both ground shock and airblast pressure on nearby structures. The ground shock usually arrives at a structure foundation earlier than airblast pressure because of the different wave propagation velocities in geomaterials and in the air. However, ground shock and airblast might act on the structure simultaneously, depending on the distance between the explosion center and the structure. Therefore, an accurate analysis of structure response and damage to a nearby surface explosion should take both ground shock and airblast pressure into consideration. The current practice usually considers only airblast pressure. Many empirical relations are available to predict airblast pressure. Most of them, however, only predict peak pressure values. In this experimental study, the experimental relationships of simultaneous ground shock and airblast forces have been obtained which can be easily applied in structural response analysis.

Study of blast-induced ground shock due to underground explosion has also been quite extensive in the last two decades. Both continuum and discontinuum models have been used to simulate blast-induced stress wave in rock masses [1]. The basic characteristics of ground shocks induced by surface explosions are short duration, large amplitude and high frequency excitations [2]. The response in the forced vibration phase includes high frequency vibration modes with small displacement but large acceleration, thus inducing high inertial shear force. However, the free vibration response is dominated by lower frequency modes with lager displacement but smaller acceleration.

1.1. Scope of Impulse Loads in ACI Standard 359

ACI Standard 359 "Code for Concrete Reactor Vessels and Containments" [3] deals with the impulse loads as time dependent loads e.g. the dynamic effects of accidental pressure, the effects of pipe rupture reactions and Jet impingement loading etc. Although the U.S. Regulation does not require consideration of explosions due to terrorist attack and other act of war in the design of Nuclear Power Plant structures, other countries postulate and consider such explosions [4].

2. EXPERIMENTAL SETUP

A 1:25 scale model of a typical reactor containment structure was constructed to determine the experimental relationships of airblast pressure time history as a function of surface explosion charge weight, distance to structure, structure height, as well as the simultaneous ground shock wave history. The success of the experimental program depends in part on the ability to accurately measure reflected pressure and to collect acceleration data from wall-mounted accelerometers.

Following equipments were used after calibration:

(1) A self-contained shock-hardened data acquisition, HDAS system was used to record data. The entire system, including transducer and two battery packs, are fitted inside a circular canister 6-cm diameter and 15-cm deep. Each gauge used in the test was connected to an HDAS system. The four external wires—ARM, CALIBRATION, TRIGGER, and GROUND—are expendable at zero time. Therefore, the system is capable of obtaining data even though the cables may be destroyed during the event. The system uses internal battery power, thus allowing for nonvolatile memory retention during and after the test. The system will capture the beginning of the waveform by using 16 ms of pre trigger data. A g-sensitive switch acts as a trigger and normally closes at 350 g's or the system can be triggered by a 5 volt pulse. The sampling rate is 100 KHz to 1 MHz.

(2) Kulite HKS-375 pressure transducers were used to measure pressure time-domain waveforms on the containment wall. The gauge dimensions are 16 mm long x 8 mm diameter. The gauges were screwed into a steel mount and then mounted into a pipe flush-mounted with each wall section. The pipe was cast into the wall sections during construction. Each pressure gauge was mounted at the center point of the containment wall in front of the blast wave.

(3) Accelerometers: Endevco series 7270A-6K, 6000 g capacity piezoresistive accelerometers were used on containment wall to measure accelerations of the wall. The dimensions of these accelerometers are 14x7x3 mm. Each accelerometer was mounted to a shock-mount plate, and the shock-mount plate was attached to the wall panels with screws. Three accelerometers KYOWA AS-GB were used to measure the dynamic response of the structure. A dynamic strain amplifier KYOWA DPM-612B amplified the signal generated by the accelerometers. A data acquisition board PCM-DAS16D/16 of 100 KHz was mounted on a notebook computer in order to record and process the signals by means of the program HP VEE 5.0.

(4) The seismograph used was Geosonic 2000DK.

The seismograph recording the blast event provides three different vibration readings on three channels. Each channel represents an axis of particle movement. These axes that are recorded by the seismograph are: radial/longitudinal, vertical and transverse. The vertical axis is that which represents the vertical movement of the ground particles. The radial or longitudinal axis represents the ground movement that runs from the blast to the transducer at right angle to the radical channel. In order to collect accurate data, the following conditions and criteria were ensured necessarily.

(i) The geophones (transducers) were firmly anchored by spiking.
(ii) The longitudinal channel pointed directly at the blast and bearings were recorded by coordination.

(iii) The seismograph was properly programmed, low enough to be triggered by blast vibration and high enough to minimize any occurrence of false event. The trigger level in our case was 1.0 mm/s for the geophone and 120 decibels for the microphone.

3. OVERPRESSURE IN THE FREE AIR FROM SURFACE EXPLOSIONS

The experimental values of shock wave propagation in the air from explosions have been obtained. The explosive (TNT) in a spherical shape is placed on the surface of the saturated sandy clay. The TNT charge weight used in experimental work is, 1, 3, 5, 15, 25 and 50 Kg respectively. The pressure time histories in each case in the air at the target points directly above the ground surface are recorded until the cracks appeared on the concrete surface. The experimental output provides the shock wave front arrival time T_a, the rising time from arrival time to the peak value Tr, peak pressure P_{so}, the decreasing time from peak to the ambient pressure T_d. Based on these data, following empirical attenuation relation for peak air pressure at a hemispherical front has been obtained.

3.1. Peak Air Pressure in the air (P_{so})

$$P_{so} = 1.026\,(R/Q^{1/3})^{-1.96}, \qquad 12 \geq R/Q^{1/3} \geq 1 \text{ (MPa)} \qquad (1)$$

where

R is the distance in meters measured from the charge center and

Q is the TNT charge weight in kilograms.

3.2. The Shock Wave Front Arrival Time Ta

The best fitted function of the arrival time in terms of distance and charge weights is

$$T_a = 0.56\, R^{1.4} Q^{-0.2} / C_a \quad \text{(s)} \qquad (2)$$

where

C_a is the sound speed in the air, which is 340 m/s.

3.3. The Rising Time for Pressure to rise suddenly from zero to peak value (T_r)

Based on the experimental data, the best fitted relation is

$$T_r = 0.0046\,(R / Q^{1/3})^{0.92} \quad \text{(s)} \qquad (3)$$

3.4. The Decreasing Time for the pressure to decrease from its peak value to the ambient pressure (T_d)

Using the experimental data, an empirical attenuation relation for the decreasing time is derived as

$$T_d = 0.0013\,(R / Q^{1/3})^{0.89} Q^{0.52} \quad \text{(s)} \qquad (4)$$

3.5. The Duration of the positive pressure phase of the shock wave (T)

$$T = T_r + T_d$$

$$T = 0.0046\,(R / Q^{1/3})^{0.92} + 0.0013\,(R / Q^{1/3})^{0.89} Q^{0.52} \quad \text{(s)} \qquad (5)$$

4. GROUND SHOCK WAVE FROM SURFACE EXPLOSIONS

4.1. Peak particle acceleration (PPA)

The best fitted PPA of surface ground motion as a function of charge weight and distance values determined through experiment is

$$\text{PPA} = 4.089\, R^{-1.3} Q^{0.83} \quad \text{(g)} \qquad (6)$$

4.2. Arrival time (t_a)

From the experimental data, the arrival time at a point on ground surface with a distance R from the charge center can be found by the following relationship

$$t_{\mathrm{a}} = \frac{0.52R^{1.26}}{Cs\,Q^{0.01}} \quad \text{(s)} \qquad (7)$$

where

Cs is the seismic velocity of the soil .

In our case, the seismic velocity of saturated sandy clay is 1524 m/s.

4.3. Shock Wave Duration (t_d)

Shock wave duration t_d is defined as

$$t_{\mathrm{d}} = t - t_{\mathrm{a}}$$

$$t_{\mathrm{d}} = 0.0056\, R^{0.52} \quad \text{(s)} \qquad \text{(From the experimental data)} \qquad (8)$$

4.4. Time lag between ground shock and airblast pressure arrival at structures (T_{lag})

From the experimental relationships obtained in (2) and (7), the time lag between the ground shock and airblast pressure reaching to the structure can be determined by

$$T_{\mathrm{lag}} = T_{\mathrm{a}} - t_{\mathrm{a}} = 0.56\, R^{1.4} Q^{-0.2}/C_{\mathrm{a}} - \frac{0.52R^{1.26}}{Cs\,Q^{0.01}} \quad \text{(s)} \qquad (9)$$

It is evident that the time lag is not only related to distance from the charge center and charge weight, but also to wave propagation velocity in the air and at the site. At the same distance, the larger the charge weight, the shorter the time lag.

5. CONCLUSIONS

It is concluded that an accurate analysis of structural response and damage of structures to a nearby external explosion requires simultaneous application of ground shock and air blast pressure time history parameters. The research work and the equations drawn may be utilized for the design of AWCR against external explosion.

REFERENCES

[1] WU C, Hao H, Lu Y, Zhou YX, Characteristic of wave recorded in small scale field blast tests in a layered rock soil medium, Geotechnique 2003; 53(6): 587-99

[2] R.P. DHAKAL, T-C. Pan. Response characteristics of structures subjected to blasting induced ground motion. International Journal of impact Engineering 28(2003) , 813-828

[3] ACI 359-01, Code for Concrete Reactor Vessels and Containment, CC 342

[4] SAEED. A, Hamid M., Javed I., Shoaib A. Identification of potential for explosions in nuclear power plants 18th Int. Conference on structural Mechanics in Reactor Technology (SMIRT) 2005 p. 2624-2630