Tunnelling and Underground Space Technology 24 (2009) 119–125

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Internal separation distances for underground explosives storage in hard rock

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ARTICLE INFO

Article history:
Received 8 January 2008
Received in revised form 15 April 2008
Accepted 27 May 2008
Available online 7 July 2008

Keywords:
Underground storage
Explosives storage
Separation distance

ABSTRACT

Most recent studies on underground explosives storage have focused their attention on external safety distances, mostly inhabited distances for airblast, debris, and ground shock. Internal distances in prevailing codes generally deal with the need to prevent sympathetic detonation as a result of propagation by rock spall impact, or to prevent damage in an adjacent chamber in the event of an accidental explosion. For complex facilities, guidelines on separation requirements are often lacking. Also, there are several inconsistencies in the current separation requirements. This paper attempts to fill in the gap and rationalise the separation requirements for the various components of an underground storage facility. Recommendations will be made based on a comprehensive review of tunnel damage and results from large-scale tests.

1. Introduction

Storage of explosives and ammunition underground offers many advantages in terms of safety and protection. The safety design of an underground storage facility is usually based on the accidental explosion of a certain net explosives quantity (NEQ). The NEQ is then the basis for the internal and external safety distances.

If there is more than one chamber sited next to each other, the rock separation between the two adjacent chambers must be sufficient to prevent a sympathetic detonation or damage of contents in an adjacent chamber, depending on the design requirements. In complex facilities, there are often needs for other kinds of separation distances. For example, the rock separation between a chamber and the main tunnel is often a key consideration in the layout design. Also, there may be cases where other tunnel systems nearby (e.g. independent storage clusters or control centre) which must remain fully functional with no interruption of operations in the event of an accidental explosion. The overall internal safety design must also consider the effects of airblast and heat propagation in a tunnel system if two chambers are connected by a tunnel. Blast doors are often used for such purposes.

The chamber separation distances required to prevent propagation or damage of contents are generally a function of the ground shock loading and rock type. For a given rock type, ground shock loading at a given distance is a function of the NEQ as well as the loading density in the chamber. Most currently available standards give the required separation distances as a function of the NEQ only. Seldom are the effects of loading densities considered. Based on results of field tests and analyses of ground shock effects and sympathetic detonation, it will be demonstrated that the current safety requirements for internal separation may be overly conservative for storage in strong rock and a more rational approach to determining the separation distances is possible. For this paper, it is assumed that the rock cover is sufficient to prevent lifting of the overburden and thereby creating a direct line of sight between adjacent chambers.

2. Criteria for internal separations

Currently, two types of chamber separation distances are generally specified in existing codes (DoD, 1999; NATO, 1999). The first is to prevent propagation of detonation by the impact of rock spall against the munitions. The second is to prevent damage of the contents in an adjacent chamber from the rock spall.

2.1. Prevention of propagation by rock spall

When no special protective construction is used, the minimum separation distance, D_{cp}, to prevent propagation of detonation by the impact of rock spall against the munitions is

$$D_{cp} = 0.6Q^{1/3} \quad (1)$$

where D_{CP} is the rock separation, m and Q is the explosives quantity, kg.

According to DOD 6055.9-STD (1999), the above separation distance is for loading densities up to 17 lb/ft^3 (about 270 kg/m^3).

Both the DOD 6055.9-STD and NATO Manual also provide for a 50% reduction in separation distance to $0.3Q^{1/3}$ if a protective

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doi:10.1016/j.tust.2008.05.005

construction is provided inside the receptor chamber. However, they do not give specifications on the type of protective structures.

2.2. Prevention of damage by rock spall

For protection of the contents in an adjacent chamber from damage, the minimum separation distance for strong and moderately strong rock with loading densities up to 50 kg/m^3 is given as follows:

$$D_{cd} = 1.0Q^{1/3} \quad (2)$$

For loading densities greater than 50 kg/m^3 in moderate to strong rock, the required separation distance is

$$D_{cd} = 2.0Q^{1/3} \quad (3)$$

The 1.0$Q^{1/3}$ separation for loading densities less than 50 kg/m^3 was a revision from 2.0$Q^{1/3}$ based on results of the US/ROK programme in which tests were conducted at loading densities of up to 50 kg/m^3. As there were no data for greater loading densities, the DOD left the separation distance D_{cd} at 2.0$Q^{1/3}$ for loading densities greater than 50 kg/m^3. In this case, there will be a jump in separation distances at a loading density of 50 kg/m^3.

For weak rock, at all loading densities, the separation distance is For limestone:

$$D_{cd} = 1.7Q^{1/3} \quad (4)$$

For sandstone:

$$D_{cd} = 1.4Q^{1/3} \quad (5)$$

It is interesting to note that most of the tests in the US/ROK programme were conducted in limestone, which was actually treated as hard rock in the revision of the US DoD standard.

In no case, the chamber separation shall be less than 5 m (Joachim, 1992). This requirement is presumably for rock engineering requirements. However, a more rational design can be provided for the rock engineering requirement based on the rock mass strength and the estimated tributary load on the separation, which can be treated as a long rock pillar.

2.3. Inconsistencies in current codes

A careful examination of the above equations shows that the following inconsistencies exist in the current codes.

- For prevention of propagation, there is a jump on rock separation requirements from 1.0$Q^{1/3}$ to 2.0$Q^{1/3}$ at a loading density of 50 kg/m^3.
- For prevention of damage of contents, there is no provision for a similar reduction in separation with a protective structure as for the prevention of propagation.
- The separation distance equations do not take into account the effects of chamber loading density, with the exception of the two different equations at a loading density of 50 kg/m^3.
- There is no provision for different rock conditions for the prevention of propagation. If this equation holds true for all rock types, then it must be concluded that it is conservative for strong rock.
- For prevention of damage, the rock type definition seems rather confusing, with limestone and sandstone defined as weak rock. Both limestone and sandstone can be strong or weak, depending on the rock mass conditions.

3. Large-scale testing

3.1. Test layout

From 2000 to 2001, several large-scale tests were conducted in a rock tunnel facility in Älvdalen, Sweden, site of the existing Klotz Group tunnel (Chong et al., 2002). Fig. 1 shows the layout and chamber sections of the tunnel facility.

The tunnel facility was constructed in a rock mass consisting of mostly red porphyry syenite with some grey granitic intrusion. Fresh intact rock has uniaxial compressive strengths of 200–250 MPa and uniaxial tensile strengths of 12.5–17.5 MPa. The rock mass quality is considered "good", with average Q values of 15–20.

The test facility consists of a detonation chamber connected by a series of tunnels. Adjacent and parallel to the chamber is a slot tunnel at criterion separation distance of 0.6$Q^{1/3}$ to test and monitor the response of an adjacent chamber (Fig. 1b). The average rock cover over the chamber area is about 100 m. The chamber has a width of 8.8 m, a height of 4.2 m, and length of 33 m. The slot tunnel is 2-m wide and has the same height of the chamber. The main tunnel connecting the chamber and slot is 4.5 m wide. The actual separation between the chamber and slot tunnel is about 13 m based on a maximum net explosives quantity (NEQ) of 10 tons. The rock separation between the chamber end and the main tunnel is based on 0.4$Q^{1/3}$, or about 9 m.

As the tunnel facility was designed to last through four years of explosion testing, including fragment loading, the dynamic support design was a major consideration. Dynamic rock bolts (Ansell, 1999) of 2.5-m long were used to support the chamber and the rock surfaces within a distance of 13 m (0.6$Q^{1/3}$) from the detonation chamber walls. In the detonation chamber, shotcrete was applied in two layers, with a wire mesh in between.

Details of the tests and instrumentation are discussed in a separate paper (Chong et al., 2002). This paper will only discuss results of ground shock measurements and observations of tunnel damage related to the following two tests:

(a) Test #3 – 10-ton bare TNT charge placed in 10 cubes (of 1-ton TNT each) distributed in the chamber with the charge centre at 900 mm from the floor.
(b) Test #4b – 10-ton TNT in 1450 rounds of 155 mm shells placed in 10 tables (with the same 1-ton TNT each), with the charge centre at 800 mm from the floor. The weight ratio of steel to TNT for these cased charges is about 5.2 to 1, giving a total of 52 tons of steel fragments.

The chamber loading density for both tests is 10 kg/m^3.

3.2. Ground shock instrumentation

Near the detonation chamber, ground shock gauges were installed in the following locations (Fig. 2):

(a) A horizontal hole perpendicular to the chamber axis.
(b) A vertical hole above the chamber centre.
(c) Along the wall of a slot tunnel at 13-m from the chamber wall.

Strain gauges were also installed on two dynamic rock bolts installed along the middle of the slot wall.

3.3. Results and observations

Results of ground shock measurements from Tests #3 and #4b are plotted in Fig. 3, along with the PPV equation for fully coupled