VIBRATION OF TUNNEL DUE TO ADJACENT BLASTING OPERATION

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1. Introduction

In recent years, the construction of utility tunnels has been quite active because of the effective use of land and the settlement of environmental problems. And the demand will increase more in the future. Under these circumstances, it is quite often necessary for a newly constructed tunnel to cross three-dimensionally with an existing old tunnel in the underground medium. When the construction works are conducted by blasting, much attention must be paid to the blasting operation in order not to cause any serious damage on the existing tunnel.

Dynamic behaviors of underground structures like tunnels due to blasting have not yet been clearly understood. Therefore, there are difficulties in establishing controlled blasting techniques. Determinations of charge weight, its pattern and design criterion for vibration of structure are based on previous experiences.

In order to establish controlled blasting techniques to avoid damage in an adjacent tunnel, the dynamic behavior of the tunnel under blast excitation must be first understood. For this purpose, some field works have been conducted. This paper is concerned with the results of these field experiments. This consists of two parts, the first is concerned with the dynamic behavior of two unlined tunnels which three-dimensionally cross each other in the underground medium, the second part is for the dynamic behavior of the concrete lining of tunnels due to an adjacent blast, and much attention is paid to discussing the relation between the particle velocity and the strain in the lining.

2. Dynamic Behaviors of Two Unlined Tunnels

2.1 Test Site

The test site where the experimental works have been conducted is shown in Fig. 1. There are two tunnels embedded in this site; one is designed as a water supply tunnel (called Tunnel A), and the other is for an underground subway (called Tunnel B). Both tunnels are under construction, so that no liners are installed as yet. The crossing angle of these two tunnels is about 78° in a level plane. The clearance between the two tunnels is 29.7m at the excavation of a pilot tunnel, which is located at the bottom of Tunnel B, and 24.5m at the excavation of the upper part of Tunnel B. The underground formation around the tunnels consists of granite, and the propagation velocity of the longitudinal wave is approximately 3.0 ~ 3.7km/s.

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2.2 Instrumentation

The particle velocities on the surface of the tunnels were measured by electromagnetic-type velocity gages (Geo-space; natural frequency $f_0 = 4.5$ Hz and $8$ Hz). The data are recorded on an electromagnetic oscillograph through a direct current amplifier. The velocity gages were directly mounted on the bottom rock surface of both tunnel A and B with cement mortar. The blasting operation was done only at the face of tunnel B and all measurements were taken at the same time for each blast.

2.3 Results and Discussions

(a) Comparison of Particle Velocity in Tunnel A and Tunnel B

Particle velocities measured at Tunnel A are compared with those at Tunnel B, as shown in Fig. 2. These measurements have been obtained for blasting operations at three different positions of the face of Tunnel B, but the measuring points in both tunnels are located at the same distance from the blast zone. Time-delay shots are used for blasting. The results are plotted against each shot.

Fig. 2 (a) shows the ratio of the vertical component in Tunnel A against the horizontal component in the direction of the axis of Tunnel B, where the horizontal component usually gives the maximum value. On the other hand, Fig. 2 (b) shows the ratio of the vertical component in Tunnel A against the vertical in Tunnel B. It can be seen from Fig. 2 (b) that the magnitude of the particle velocity in Tunnel A may become more than ten times greater than in Tunnel B, and the vertical component of Tunnel A gives a 2-7 times greater magnitude than the horizontal component, depending on the location of blast zone. The maximum value of this ratio is obtained when the face of the tunnel approaches to within 30m of the crossing point, and this ratio tends to decrease as the tunnel face approaches the crossing point and passes through it.

Fig. 2 (b) shows the ratio of the vertical component in Tunnel A against the horizontal component in the direction of the axis of Tunnel B, where the horizontal component usually gives the maximum value. On the other hand, Fig. 2 (c) shows the ratio of the vertical component in Tunnel A against the vertical in Tunnel B. It can be seen from Fig. 2 (c) that the magnitude of the particle velocity in Tunnel A may become more than ten times greater than in Tunnel B, and the vertical component of Tunnel A gives a 2-7 times greater magnitude than the horizontal component, depending on the location of blast zone. The maximum value of this ratio is obtained when the face of the tunnel approaches to within 30m of the crossing point, and this ratio tends to decrease as the tunnel face approaches the crossing point and passes through it.
In Fig. 5, particle velocity magnitudes in both tunnels are plotted against the distances between the blast zone and the measuring points. It is obvious that the regression lines in these figures are quite different from each other. Vibration of Tunnel A decreases more rapidly with distance than Tunnel B. These differences come from the different wave paths from the blast zone. Assuming that there is similar geometrical relation between the case as shown in Fig. 5(b) and the case where the tunnel face approaches a measuring point, as shown in Fig. 4, the following relation is valid among particle velocity $v (\text{m/s})$, charge weight $W (\text{kg})$ and distance $r (\text{m})$.

$$v = C W^{1/3} r^{-2/3}$$

where $C$ is a constant, depending on the method of blasting, nature of rock and type of charge. It is seen that the constant $C$ is a factor giving the magnitude of energy transmitted into the medium. The results calculated show that the constant $C$ decreases as the blast zone approaches the measuring point. The results are plotted as a function of the angle between the tunnel axis and the direction to the measuring point, as shown in Fig. 6.

It may be concluded that the energy is not uniformly propagated in all directions, but much of the energy is transmitted in the direction of tunnel progression.

3. Effects of Blasting on Tunnel Lining

3.1 Test Sites

Field experiments have been conducted at two different sites having tunnels with concrete linings. One is a utility tunnel embedded beneath building land (called Site 1). The other is a bypass tunnel at a dam construction site (called Site 2). Configurations of the blast holes, charge weight as well as the geometrical relation of both tunnels are shown in Fig. 7(a) and (b). The types of charge were dynamite and ANFO. The charges were fired from a farther point, so as not to damage the ground through which wave travelled. Rocks around the tunnel are granite at Site 1 and limestone at Site 2. For both sites, there are no surface soil layers. The propagation velocities of the longitudinal wave at Site 1 and 2 are in the range of $2.5 - 3.5 \text{km/s}$ and $2.5 - 4.4 \text{km/s}$, respectively.
Dynamic Behaviour

3.2 Instrumentation

The measuring devices used in these field works were electromagnetic-type velocity gages (Geospace: natural frequency $f_n = 4.3Hz$, mini-accelerometers (Kyowa: natural frequency $f_n = 750Hz$, max. 50G) and SR-4 strain gages (G.L = 67mm). These measuring devices were mounted on the internal surface of the concrete lining, and the gage arrays are shown in Fig. 8. The vertical and horizontal components of particle velocity and acceleration were measured. The horizontal components were all in a direction perpendicular to the tunnel axis. For strain, circumferential components along the internal surface of the lining were obtained, and the radial components within the lining were measured by split SR-4 strain gages.

Fig. 7  Section View of Test Sites

3.3 Results and Discussions

(1) Seismogram of Particle Velocity and Propagation Equation

Some of the seismograms of particle velocity measured at the ground surface and on the internal surface of the lining, are shown in Fig. 9. The data for the lining are obtained at the measuring point facing the blast zone. It is obvious that particle velocity on the ground surface is strongly influenced by the free boundary of the ground. The data for both Site 1 and 2 are plotted in Fig. 10, to determine propagation equations relating the magnitude of peak particle velocity to distance. In these figures, the magnitudes of the initial peak and the maximum after the initial are included only in the figure showing the ground surface measurement.

The empirical propagation equation may be written in the following general form,

$$v = C \cdot r^{-\alpha}$$

where $v$ is particle velocity, $r$ is distance between blast zone and measuring point, $W$ is charge weight, and $C, \alpha$ are all positive coefficients.

It is noted that the regression lines shown in Fig. 10 are similar, so that the decay exponent $\alpha$ can be assumed to be $\alpha = 2$ for both cases of the ground surface and the lining, i.e. the magnitude of particle velocity decreases with increase of distance.

(2) Particle Velocity Distributions on Lining

Distributions of particle velocity on the lining for Sites 1 and 2 are shown in Fig. 11 and 12, respectively. Fig. 11 is the result of the blasting operation at a distance of 3m from the lining, and Fig. 12 is for 15m. These figures are obtained by plotting the particle velocity at each measuring point, as a vector, originating from the deformed lining axis. It is obvious that the maximum particle velocity on the lining may occur at a point facing the blast zone or at its crown.

Fig. 8  Location of Measuring Points

Fig. 6  Orientation of Energy Propagation from Blast Zone
(3) Relation between Particle Velocity and Strain on Surface of Lining

Strain is not associated with rigid motion but particle velocity contains a component of rigid motion. The particle velocity essentially differs from the strain. Therefore, the maximum strain does not necessarily occur at the same place as where the particle velocity becomes a maximum. Some of the seismograms of circumferential strain on the surface of lining are shown in Fig. 13. The distributions of particle velocity and strain on the internal surface of the lining for Site 2 are given in Fig. 14.

It is obvious from the experimental results shown in Fig. 14 (a) that the radial component of particle velocity gives a maximum value at θ = 90°, i.e., at the arch crown. On the other hand, the maximum value of circumferential strain is obtained at roughly θ = 45° or 150°. It is noted from these results that the point giving the maximum particle velocity does not coincide with one giving the maximum strain. This is also obvious from the theoretical results shown in Fig. 14 (b). These theoretical solutions are for the case of sinusoidal harmonic motion. But it has been verified that the difference between sinusoidal harmonic solution and one for a single sinusoidal pulse becomes negligibly small if the wave length is more than three times larger than tunnel diameter.

Experimental results for the radial component of particle velocity give the maximum value at the crown (θ = 50°), but they differ from the theoretical solutions in which the maximum value occurs at the point facing the blast zone (θ = 55°). This discrepancy may arise as follows: a) There usually exists an opening between the arch crown and the surrounding medium so that the radial particle velocity at the crown becomes extremely large. b) There is much loosening in the medium behind the arch crown.
Dynamic Behaviour

Fig. 11 Particle Velocity Distributions in Concrete Lining (Site 1)

Fig. 12 Particle Velocity Distributions in Concrete Lining (Site 2)

Fig. 13 Seismogram of Circumferential Strain (Site 2)

Effects of Blasting

Fig. 14 Distribution of Particle Velocity and Strain (Site 2)
Fig. 15 shows the relation between particle velocity and strain, both of which are obtained at the same time and at the same measuring point. From this figure, it is clear that the strain cannot be uniquely determined by particle velocity because of the different distributions along the lining. Plotting the maximum particle velocity against the maximum strain, even though they occur at different points, gives Fig. 16, which shows a linear relation between these two magnitudes. The place where the measurements are obtained is of fundamental importance in discussing the relation between strain and particle velocity.

The strain $\varepsilon$ is often estimated through particle velocity $\nu$ by the following equation:

$$\varepsilon = \frac{\nu}{C} \quad (3)$$

where $C$ is usually chosen to be constant. But, according to the theoretical solution, the constant depends on the geometrical relation of the tunnel, relative rigidity of lining and medium, and frequency of vibration, as shown in the following form:

$$\frac{1}{C} = \frac{G_1 k_1^2 |S(r)|}{2\pi f |H_0^1(k_1 r)|} \frac{\sigma^*}{E_0^*} \quad (4)$$

where,

- $S(r) = H_0^1(k_1 r)/(1/k_1^2 - 1)$
- $k = \sqrt{2(1-\nu)/(1-2\nu)}$
- $\nu$ : Poisson's ratio of medium
- $k_1$ : $2\pi f |V_p|$
- $\nu^*$ : Concentration factor of particle velocity
- $H_0^1$ : 1st order Hankel function of 2nd kind
- $r$ : Distance from blast zone

The linear relation between the maximum particle velocity and the maximum strain, shown in Fig. 15, gives that the particle velocity for failure of the lining becomes approximately 35 km/s, with an assumption that tensile stress for failure of concrete is 200 kgs/m². In fact, it has been reported that crack initiation occurred on a concrete tunnel lining at the particle velocity of 35.8 km/s.\(^3\)

(4) Radial Strain Within Lining

The strain discussed in the previous section was that on the surface of lining. The next question is what about strain within the lining. A result of the measurement is shown in Table 1, which shows the magnitude of the initial peak when the wave arrives at the lining. These data are those for the measuring point facing the blast zone.

<table>
<thead>
<tr>
<th>Distance from internal surface (cm)</th>
<th>Tangential component on the surface</th>
<th>Radial component within lining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain ($x10^{-6}$)</td>
<td>0.0*</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>0.0**</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>32.5</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>45.5</td>
<td></td>
</tr>
</tbody>
</table>

* Tunnal axis direction
** Circumferential direction

( - : Compression, + : Tension)
It is noted from the result that the radial strains within the lining are all compressive for the initial peak, and their magnitudes increase at measuring points near to the internal free surface of the lining. On the other hand, strains at the surface of the lining are tensile, the magnitudes of which are larger than those of compression within the lining. It is concluded, therefore, that the maximum tensile strain occurs at the surface.

4. Conclusions

The results obtained herein are summarized as follows:

1. Even though the distances from the blast zone are the same, a large vibration may occur in an existing tunnel (Tunnel A), whereas in a newly constructed tunnel (Tunnel B) where the blasting operation is conducted. Therefore, if the measurements obtained in Tunnel B are used for estimating the vibration of Tunnel A, care in estimation is necessary, because it is not on the safe side.

2. When the face of Tunnel B approaches Tunnel A, blast control is of much importance, so as not to damage Tunnel A, in comparison with when the face passes through or leaves the crossing point.

3. The slopes of regression lines for particle velocity versus distance are approximately the same for both measurements obtained on the surface of the concrete tunnel lining and on the ground surface.

4. The vertical component of particle velocity at the arch crown of the lining gives the maximum value. This may be due to an opening or lowering of medium behind the arch crown. Apart from the arch crown, the particle velocity in any position facing the blast zone is also remarkably high.

5. The place where the maximum strain occurs is not necessarily the same as where the particle velocity gives the maximum value.

6. The maximum strain seems to be proportional to the maximum particle velocity, and its proportionality constant may be a function of the geometrical relation, relative rigidity of lining and ground medium, and frequency, even though they occur at different places on the lining.

7. The radial strain within the lining facing the blast zone is compressive at the initial peak and its magnitude is always small, compared with the tensile strain obtained at the surface of the lining.

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References


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