Study on the Shotcrete Cumulative Damage Caused by Blasting

Renliang Shan[1], Yongwei Song[1,a,*], Chi Meng[1], Pengcheng Huang[1], Mengnan Wang[1], and Shupeng Zhang[1]

[1]*School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing, China*

a. 895027891@qq.com

**Yongwei Song*

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Abstract: In order to study the cumulative damage law of new shotcrete caused by tunnel blasting, the equivalent charge weight, equivalent distance and acoustic velocity of multiple blasting were statistically analyzed. It is found that the cumulative damage of shotcrete caused by blasting increases gradually with the increase of the number of cycles. After 4 cyclic blasting, the cumulative damage of No.1 measuring point near the explosion source is the largest, 0.274, which is greater than 0.19 of the standard damage threshold, but there is no instability failure of the shotcrete. When the distance between the measured point and the construction face is about 20 m, the cumulative damage is about 0.05, the vibration velocity and the damage inflection point appear. There is a good power function correlation between damage increment and vibration velocity.

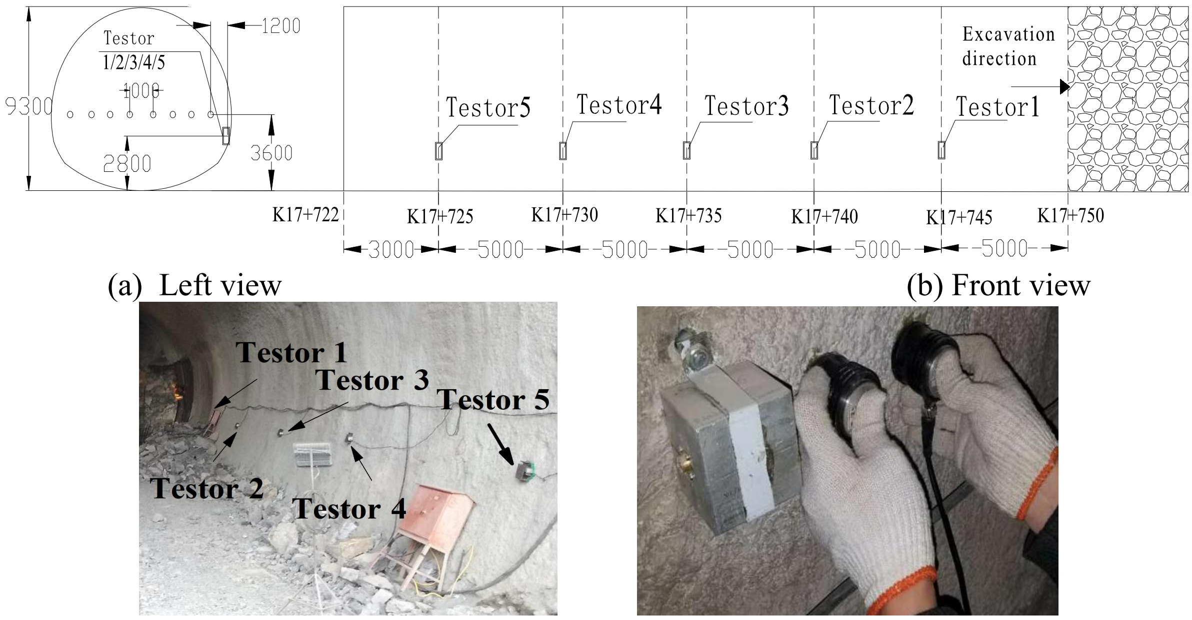
1. Introduction

At present, the research on the influence of blasting vibration load on shotcrete is mainly mass shotcrete, which mainly monitors the change of mechanical parameters of each measuring point caused by blasting, and determines the safety vibration speed of blasting under different age conditions, so as to provide theoretical basis for construction[1, 2, 3, 4].However, it is obviously not feasible to control the blasting effect only from the safe vibration speed, and the blasting effect is not only affected by the dosage, but also closely related to the hole arrangement scheme, detonation distance, explosive performance and so on[5]. Based on the field investigation data, the model test was established and the influence of cyclic blasting on the mechanical properties of shotcrete at different ages after tunnel excavation was studied[6, 7]. The influence of shaft blasting on shotcrete based on model test was studied, and explained theoretically the influence of blasting on the mechanical properties of shotcrete at different ages[8, 9]. Combined with damage theory and numerical simulation, Ding TS[10] studied the effect of blasting air wave on cumulative damage of shotcrete at different ages, and put forward the allowable damage threshold of shotcrete. Based on isotropic, homogeneous and other basic assumptions, Chen M[11] introduced elastic waves to study the influence of elastic P-wave and S-wave on the failure form and safe vibration velocity of shotcrete, which provided the basis for engineering. Relative to the impact of blasting on the mechanical properties of shotcrete model and field test research, domestic and foreign scholars have also made great achievements in theoretical research [12, 13].

In this paper, The reconstruction and extension blasting construction of Heiyu tunnel was taken as the engineering background, the variation rule of cumulative damage of shotcrete under the action of cyclic blasting is studied by field measurement, and its stability is evaluated so as to provide a theoretical basis for the project.

2. Monitoring Programmes

The K17+722~K17+761 tunnel has been converted and expanded into a new tunnel in the import section. A new K17+722~K17+761 interval section is the thickest 6m of the sandwich column in the original tunnel, only 3.2m thick at the entrance, and the new section of the K17+761 section intersects with the original tunnel. The main monitoring is shotcrete damage and vibration velocity of new section tunnel.



(a) Left view (b) Front view

(c) Vibration velocity monitoring (d) Acoustic velocity monitoring

Figure 1: Vibration speed and acoustic velocity monitoring scheme.

In the new tunnel hole depth 3m layout 1th sensor, 2, 3, 4th and 5th sensor interval 5m layout, sensor 1, 2, 3, 4, 5th measuring point is arranged in the arch shoulder 2.8m.Among them, the vibration velocity sensor x direction is the tunnel depth direction, y direction is perpendicular to the tunnel axis along the horizontal direction, z direction perpendicular to the tunnel axis vertical upward. The acoustic wave velocity at each vibration velocity measuring point after each blasting is monitored by RSM-SY5 acoustic tester. In order to reduce the error, the acoustic wave test is carried out at 0.1m on both sides of the vibration speed sensor respectively, and the distance of the two transducers is 0.05m, as shown in Figure 1. Since the first section of the charge is always the largest charge during the monitoring process, only one section of the hole and the position of the sensor are shown in the diagram. The distance between the right-most hole and the sensor is 1.2m, and the distance between the holes is 1m.

3. Research on Cumulative Damage of Shotcrete

The field construction generally uses segmented blasting, while the distance of multiple holes in the same section is not the same as that of the vibration sensor. Only the maximum charge and the geometric distance of the detonation center are used, ignoring the mutual influence of different hole blasting in the same section. Therefore, the maximum equivalent charge is introduced to replace the maximum charge, and the equivalent distance to replace the distance of the detonation center. The calculation formula is as follows:

$$R' = \frac{\sum_{i=1}^{n} (\sqrt[3]{q_i} r_i)}{\sum_{i=1}^{n} \sqrt[3]{q_i}} \qquad Q' = \sum_{i=1}^{n} q_i \left(\frac{R'}{r_i}\right)^3 \tag{1}$$

In the formula, R' is the equivalent distance, m; Q' is the equivalent charge, kg; q_i is the charge quantity of the i hole in the same section, kg; r_i is the distance of the distance sensor of the I hole in the same section, m.

The damage factor D is defined by the variation of acoustic velocity, as follows:

$$D = 1 - \left(\frac{v'}{v}\right)^2 \tag{2}$$

In the formula, v' is acoustic velocity after blasting, $m \cdot s^{-1}$; v is acoustic velocity before blasting, $m \cdot s^{-1}$.

By substituting the acoustic velocity, distance from blasting center and charge amount before and after blasting into equations (1) and (2), the damage degree after each blasting and the damage caused by each blasting can be obtained, as shown in Table 1. The variation of damage after blasting with the number and distance of blasting is shown in Figure 2 and Figure 3.

Table 1: Vibration and damage parameters of each measuring point.

Monitoring point	Classification	Blasting times				
		Before blasting	1	2	3	4
1	Distance from construction face/m		5	8	11	14
	Equivalent distance/m	-	8.28	10.82	13.39	16.15
	Equivalent charge/kg	-	27.51	25.18	22.05	21.78
	Acoustic velocity/(m·s-1)	1255	1166	1105	1085	1069
	Damage/D		0.137	0.225	0.253	0.274
	Damage increment/ΔD		0.137	0.088	0.028	0.022
	Vibrating velocity/(cm·s-1)		19.63	9.26	10.51	6.26
2	Distance from construction face/m		10	13	16	19
	Equivalent distance/m	-	12.62	15.41	18.22	21.12
	Equivalent charge/kg	-	24.64	24.29	21.36	21.25
	Acoustic velocity/(m·s-1)	1112	1099	1069	1055	1048
	Damage/D		0.112	0.159	0.181	0.192
	Damage increment/ΔD		0.112	0.047	0.022	0.011
	Vibrating velocity/(cm·s-1)		13.26	7.61	6.25	4.47
3	Distance from construction face/m		15	18	21	24
	Equivalent distance/m	-	17.31	20.19	23.07	26.01
	Equivalent charge/kg	-	24.18	24.11	21.21	21.15
	Acoustic velocity/(m·s-1)	1081	1062	1046	1041	1039
	Damage/D		0.076	0.104	0.112	0.116
	Damage increment/ΔD		0.076	0.028	0.009	0.003
	Vibrating velocity/(cm·s-1)		6.448	4.137	4.433	3.31
4	Distance from construction face/m		20	23	26	29
	Equivalent distance/m	-	22.13	25.06	27.97	30.93
	Equivalent charge/kg	-	24.07	24.04	21.13	21.11
	Acoustic velocity/(m·s-1)	1056	1043	1035	1030	1027
	Damage/D		0.076	0.090	0.099	0.104
	Damage increment/ΔD		0.076	0.014	0.009	0.005
	Vibrating velocity/(cm·s-1)		4.363	3.77	2.728	1.676
5	Distance from construction face/m		25	28	31	34
	Equivalent distance/m		27.02	29.97	32.91	35.87
	Equivalent charge/kg		24.03	24.02	21.09	21.08
	Acoustic velocity/(m·s-1)	1042	1032	1026	1022	1021
	Damage/D		0.068	0.079	0.086	0.088
	Damage increment/ΔD		0.068	0.011	0.007	0.002
	Vibrating velocity/(cm·s-1)		3.664	3.713	1.546	1.541

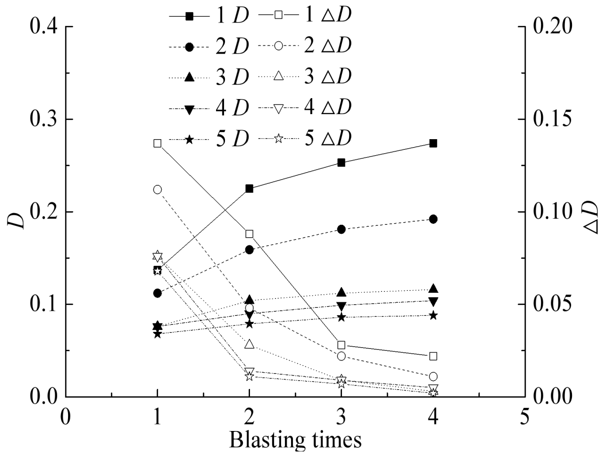


Figure 2: Variation of blasting damage and damage increment.

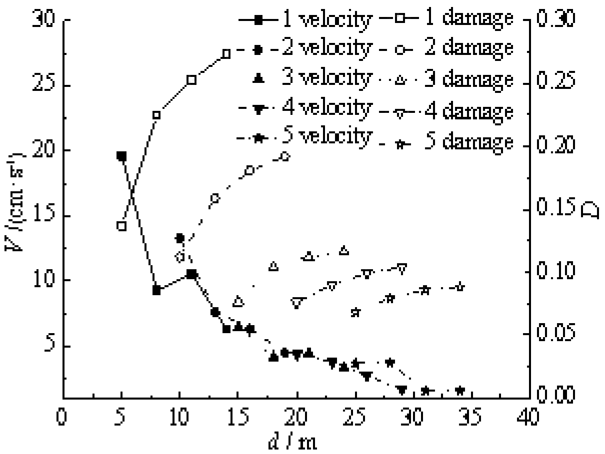


Figure 3: Relationship between vibration velocity and damage with distance.

As can be seen from Figure 2, the first blasting has the largest impact on the No.1 measuring point, and the damage caused by a single blasting is as high as 0.137. However, with the progress of construction, the distance between the No.1 measuring point and the construction face increases, and the damage caused by the second blasting is 0.225, with the damage increment of 0.088, and the damage increment of the third blasting is only 0.028. For No.2, No.3, No.4 and No.5 measuring points, the damage increment is small, and the cumulative damage caused by 4 blasting is respectively 0.192, 0.116, 0.104 and 0.088, indicating that the farther the distance from the construction face, the smaller the impact of blasting on it, and the cumulative damage of shotcrete shows a nonlinear growth trend. When the distance between each measuring point and the construction face is more than 30m, the damage increment is only 0.002, indicating that when the distance between each measuring point and the construction face is more than 30m, the impact of blasting on shotcrete is small.

As shown in Figure 3, when the distance between the measuring point and the construction face is in the 0~20m range, the cumulative damage is greater than 0.05, the blasting vibration rate attenuation is the fastest, when the distance is 14m, the damage of No.1 measuring point is 0.274, which is more than the damage failure threshold 0.19, but the shotcrete does not lose the bearing capacity. It shows that there are a lot of cracks in the shotcrete. This indicates that there are a large number of cracks in the shotcrete, and when the vibration is transmitted to the cracks, the cracks play a buffering role, the vibration energy is greatly weakened, and a series of clutter waves is generated, and the vibration velocity is sharply attenuated, indicating that the attenuation of the vibration velocity can be regarded as a macroscopic characteristic of blasting damage.

The damage of each measuring point caused by blasting presents a nonlinear growth trend with the distance, and the fitting formula is assumed to be:

$$D = a\left(\frac{\sqrt[3]{Q'}}{R'}\right)^b \tag{2}$$

In the formula, D , Q' , R' is the same as above; a, b is the undetermined coefficient.

The cumulative damage, damage increment and vibration velocity of each measuring point of each blasting were fitted and analyzed according to the equivalent charge, equivalent distance and vibration velocity of each measuring point of blasting mentioned above. The fitting results are shown in Figure 4, Figure 5 and Figure 6.

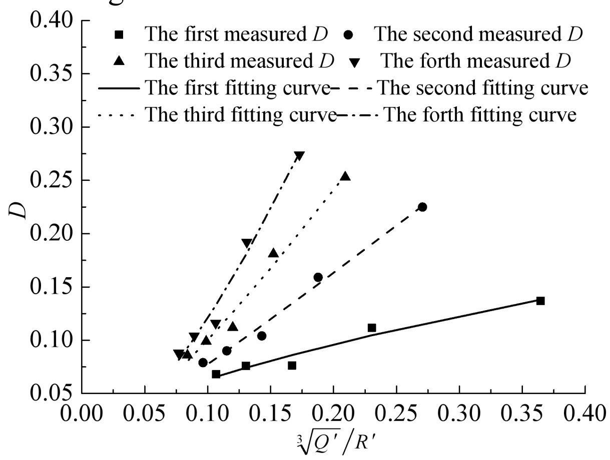


Figure 4: Fitting curve of each blasting damage.

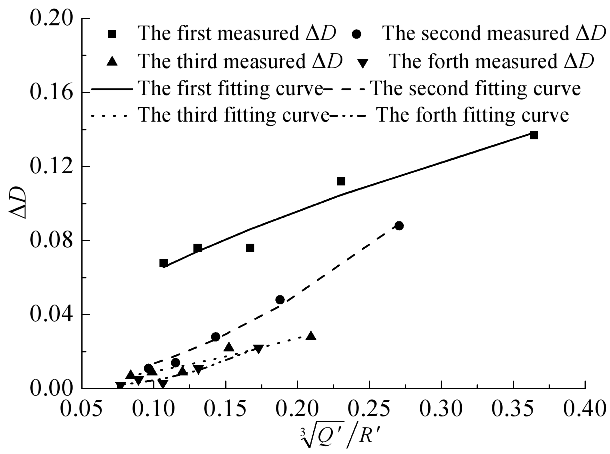


Figure 5: Damage increment fitting curve of each blasting.

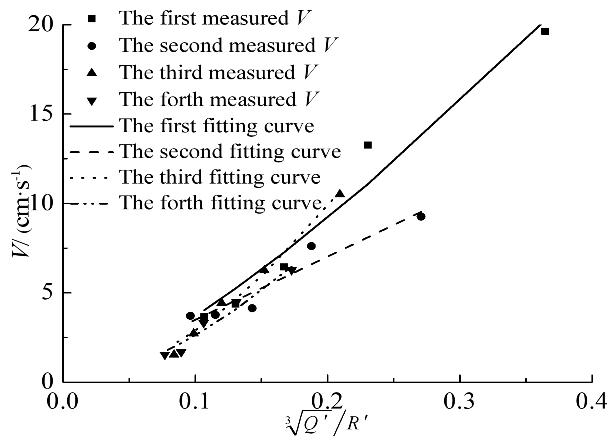


Figure 6: The vibration velocity fitting curve of each blasting.

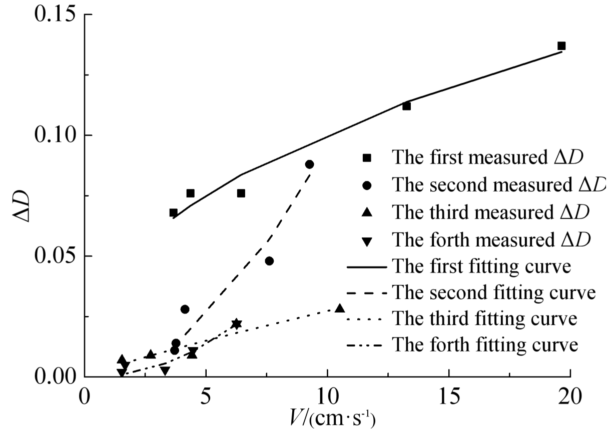


Figure 7: Variation of damage increment with vibration velocity.

$$\left.\begin{array}{llll}
\text{First blast} & & \text{Second blast} & \\
D = 0.254\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{0.605} & (R^2 = 0.941) & D = 0.921\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.075} & (R^2 = 0.986) \\
\Delta D = 0.254\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{0.605} & (R^2 = 0.941) & \Delta D = 1.054\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.890} & (R^2 = 0.989) \\
v = 72.249\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.314} & (R^2 = 0.952) & v = 35.531\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.007} & (R^2 = 0.896) \\
\text{Third blast} & & \text{Forth blast} & \\
D = 1.837\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.263} & (R^2 = 0.976) & D = 3.864\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.551} & (R^2 = 0.976) \\
\Delta D = 0.329\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.263} & (R^2 = 0.887) & \Delta D = 3.551\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{2.893} & (R^2 = 0.951) \\
v = 167.733\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.763} & (R^2 = 0.984) & v = 114.889\left(\frac{\sqrt[3]{Q'}}{R'}\right)^{1.640} & (R^2 = 0.947)
\end{array}\right\} \quad (3)$$

According to equation (3), shotcrete damage and damage increment caused by each blasting are similar to the vibration velocity attenuation function, and their correlation coefficients are all above 0.9 (the second vibration velocity attenuation correlation coefficient is 0.896 less than 0.9, but the correlation is also good). According to the analysis in Figure 5, with the increase of blasting times, the damage increment gradually decreases, the fourth damage increment of No.1 measuring point is 0.0022, while that of No.5 measuring point is only 0.002.

According to equation (3), it can be found that there is a significant correlation between damage increment and vibration velocity. When the action time of blasting stress wave is not considered, power function is adopted to fit them, as shown in Figure 7.

$$\left.\begin{array}{llll} \text{First blasting} & & \text{Second blasting} & \\ \Delta D = 0.0378 v^{0.426} & (R^2 = 0.962) & \Delta D = 0.00111 v^{1.941} & (R^2 = 0.925) \\ \text{Third blasting} & & \text{Forth blasting} & \\ \Delta D = 0.00373 v^{0.865} & (R^2 = 0.859) & \Delta D = 0.00043 v^{2.139} & (R^2 = 0.895) \end{array}\right\} \quad (4)$$

According to formula (4), four blasting damage increment and vibration velocity fitting results are good, but it can be found from Figure 7 that there is a certain difference in damage increment caused by each blasting under the same vibration velocity, which may be due to the fact that after each blasting, there is a certain difference in the damage increment caused by each blasting. The damage of surrounding rock and shotcrete is different from the damage of the previous blasting cycle, and the anisotropy is more obvious, and even if the charge is the same each time, the stress acting time produced by the blasting to the shotcrete of the same measuring point is different. Therefore, the damage increment caused by multiple blasting has not been studied in this paper as a whole.

4. Conclusions

Combined with the field test, the shotcrete cumulative damage and damage increment of the newly built tunnel are studied by introducing the equivalent charge and the equivalent distance. The conclusions are as follows.

(1)The cumulative damage of shotcrete caused by blasting increases gradually with the advance of construction, while the damage increment decreases gradually, and the damage has irreversibility. The damage increment caused by this blasting is smaller. After four cycles blasting, the cumulative damage of No.1 measuring point close to the explosion source is the largest, 0.274, which is greater than the standard damage threshold of 0.19, but there is no instability damage of the shotcrete.

(2)The fitting correlation coefficient between the damage increment and the vibration velocity caused by each cyclic blasting is greater than 0.859, indicating that the damage increment and the vibration velocity have a good power function correlation.

Acknowledgments

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References

[1] Zhu CT, Zhang ZY, Tong JY et al. Study on the influence of blasting on newly poured concrete and the control standard. Blasting. 03 (1990) 28-32.

[2] Shu DQ. Effect of blasting vibration on quality of new-laid concrete and control measures. J. Wuhan Univ. of Hydr.& Elec. Eng. 32 (1999) 5-9.
[3] Lu WB, Lai SX, Zhu CY, et al. Safety standards of blast vibrations adopted in rock base excavation of three gorge project. Explosion and Shock Waves. 21 (2001) 67-71.
[4] Lu WB, Zhang JM, Zhu CY, et al. Vibration Control in Rock Excavation Blasting near the Freshly - casted Concrete Body. Explosive Materials. 29 (2000) 28-31.
[5] Wu DL, Ye XM. A comprehensive review and commendation of blast vibration safety velocity. Chinese Journal of Rock Mechanics and Engineering. 16 (1997) 6-10.
[6] Chen YS, Li N, Lv Q. The concrete lined blasting vibration simulation test. Journal of Xi`an University of Technology. 12 (1996) 47-51.
[7] Li N, Chen YS, Lv Q. Lab test on damage behavior of the tunnel load lining under blasting. Engineering Blasting. 02 (1996) 6-10.
[8] Zhang C, Hu F, Zou S. Effects of blast induced vibrations on the fresh concrete lining of a shaft[J]. Tunnelling & Underground Space Technology Incorporating Trenchless Technology Research, 20 (2005) 356-361.
[9] Huang Q, Hu F. Test of mechanical properties of concrete under the load of blasting. Journal of China Coal Society. 21 (1996) 56-59.
[10] Ding TS, Li WX. Damage Analysis of Fresh Shotcrete under Excavating Blast Load. Chinese Journal of Underground Space and Engineering. 02 (2006) 834-838.
[11] Chen M, Lu WB. The influence of explosive stress wave on young concrete lining. Rock and Soil Mechanics. 29 (2008) 445-459+464.
[12] Tashman L, Masad E, Little D, et al., A micro structure-based viscoplastic model for asphalt concrete, International Journal of Plasticity. 21 (2005) 1659-1685.
[13] Lee V W, Karl J. Diffraction of SV waves by underground, circular, cylindrical cavities. Soil Dynamics & Earthquake Engineering. 11 (1992) 445-456.