DISTINCTIVE SETTING AND UNDERGROUND CONSERVATION ZONE OF YUNGANG GROTTOES , DATONG , CHINA

Meng Fanxing / China

Yungang Grottoes, Located in the southern edge of Wuzhoushan Mountain west to Datong City, Shanxi Province, was initiated from the First Year of the reign of Emperor Wencheng during North Wei Period of China (460 AC), and flourished from 460s to 490s. The cutting of the grottoes lasted till 520s. Representing the outstanding achievement of Buddhist cave art in China, Yungang Grottoes, Longmen Grottoes in Luoyang, Henan Province and Mogao Grottoes in Dunhuang, Gansu Province are entitled the Three Great Treasure Houses of Buddism Grotto Art in China. Yungang Grottoes extends 1 km east-west with over 18,000 m² of carved surface. The existing 252 caves and niches contain over 51,000 statues. Sculptures here are noted for their rich variety that range from the smallest, only 2 centimeters high, to the tallest – a Buddha 17-meters high. During the reign of Emperor Xiaowen of the North Wei period, the cave art in Yungang Grottoes entered its heyday. Consecutive cuttings of a dozen of large-scale grottoes were carried out in the east and north parts of the grotto zone. These grottoes demonstrate a variety of grotto types. For example, there are grottoes with central pagoda pillars, grottoes with fore- and hinder-chambers as well as grottoes with chanting passages. The figures present a wide range of themes, such as Buddhist stories, the preaching tales of Sakyamuni and so on. The great dancing scenes provide abundance of data for the studies of ancient music and dancing. The royal projects came to an end after the Emperor moved the capital to Luoyang while local bureaucracy, monks and nuns still had about 200 medium- and small-sized grottoes cut. Generally speaking, Yungang Grottoes have a magnificent scale. These Grottoes demonstrate exquisite craftsmanship that embraced the artistic achievements of the foregoing Qin and Han Dynasties while absorbing artistic characters from abroad. All this ensures Yungang Grottoes a preeminent position in the art history of China. It has been inscribed as one of the earliest Key National Monuments and then a World Heritage site due to its outstanding historical and artistic value.

From the 1960s onwards, the government made great efforts by safeguarding the site, including the demarcation of a key protection area, a general protection area and a construction control area.

The grottoes are located on the rock bed which is easily subject to weathering, with developed faults and layers. The minable coal beds are of high quality. These features made Yungang Area a favorable location for coalmines and quarries. The vibrations induced by seismic movements, underground mining, quarrying as well as train and truck transport in the surrounding area put Yungang Grottoes into a dangerous situation in which the loose rocks are about to fall from time to time, threatening the safety of visitors.

In September, 1973 the former Chinese premier Zhou Enlai and French President Georges Pompidou met and visited Yungang. In order to safeguard the event, a special "emergency reinforcement project" was carried out in order to pin up the loose suspending rocks. Due to the fragile surrounding of the Grottoes which is under weathering and the influence induced by mining activities, the emergency project could only be a temporary countermeasure to the dangerous condition. In order to measure the main threats to the Grottoes posed by vibrations coming from the surrounding area, and to find out the best solutions, we arranged vibration measurements. Different departments collaborated well in order to overcome the difficulties rose in the recordings and samplings of data. For example, while measuring the vibration induced by a full-loaded train passing the grotto area, we had to ensure that all other activities which could make disturbances really suspended, such as truck transport, underground coalmining and ground quarrying. The explosion depth and doses for underground mining could not be obtained without the cooperation of related working divisions. Finally, we worked out the report on vibration measurements in Yungang Grottoes, Datong which could be referred to in the appendix.

Studying the results collected in the measurements, the monument protecting staff realized, that for Yungang Grottoes, a site with such fragile and special surroundings, the normal aboveground protection approaches such as the demarcation of key protection area, general protection area, construction control area, the limit to the form, volume, color of surrounding structures are far from sufficient. Hence,

the breakthrough of "a underground hopper-shaped tridimensional security zone" was proposed and carried out in Yungang.

The upper peristome of this "underground security pillar" coincides with the boundary of the key protection area. Then it goes top down along the boundary taking the natural rock collapse angle of 70 degree, while the bottom boundary extends with the downward expansion of the mining operation. This security pillar forms a tridimentsional security zone under the mountain body of the grottoes within the range of which no mining activities are permitted.

After thirty years, this "underground security pillar" proved to be an ideal countermeasure to cave-in under the grotto area which poses the greatest danger to the grottoes. The invention of this "underground security pillar" demonstrates that the mature and scientific characters of the protection of historical monuments in China. In the field of prognosis and prevention from damaging threatens, the protection work in China has reached a level with great foresight and practical values.

Threats to historical monuments vary according to different geological, hydrological, and environmental background. In order to adopt the most suitable countermeasures, the main threats should be found out.

Among all kinds of vibrative influence, natural earthquakes and cave-ins during mining activities constitute the major threat to the grottoes. Natural earthquakes also lead to cave-ins in the mined-empty-areas whch bring damages to the grottoes. The concept of the "underground security pillar" could prevent to some extent the mined-empty-areas from forming, hence ensuring a solid foundation under historical monuments. With this method, both cave-ins in the mined-empty-areas and the threats from natural earthquakes could be partly eliminated.

It is suggested that the administration of World Heritage sites should be carried out with the emphases on the survey of their settings and the precautions against the threats caused by the settings. While the setting should be tridimensional, including both the above ground and underground spaces, the threats are coming from all directions. Only if successful measurements could be carried out and convincing data collected, protective countermeasures could then be found and adopted targeting specific threats.

Appendix:

Report on the Vibration Measurement at Yungang Grottoes, Datong

Preface

In order to find out the vibrating effects induced by mining explosions, ground quarries, railway and highway transport around Yungang Grottoes, thereby ascertain the scope of the protection zone, the Provincial Seismic Measurement Team undertook the vibration measurement in the Yungang Area in December, 1973, while the related data were provided by the Provincial Bureau of Culture. With the assistance by the related working units such as Hong Jiu Mine of Da Tong Mining Bureau, the Railway Bureau of Da Tong, the Highway Transport Bureau of Da Tong, Qing Ci Yao Coal Mine, Wu Guan Tun Coal Mine as well as Yungang Mining Brigade, our group of seven members carried out the task successfully during the thirty-seven days from April 1 to May 7, 1974, using three altered tromometers as measuring instruments.

Location and General Situation of Yungang Grottoes(Please refer to the Location Map with a scale of 1:250,000)

15 kilometers north of the Da Tong City, Yungang area is located at the North scarp of the Wu Zhou Mountain and distributed on the terrace on the north bank of the Shi Li River. Uplands with mild slopes dominate the surrounding area. According to the topographical characters, the cliffs were carved by the scouring movement of the Shi Li River towards North, and the direction of the scouring movement changed afterwards, therefore left the cliffs intact on which the ancients cut the grottoes.

The original designated area is 3.6km^2 with a transmeridional length of 2.275km and a meridional width of 1.565km. The coordinates of the boundary points are:

Ⅰ	x=552240	y=4441330
Ⅱ	x=554515	y=4441330
Ⅲ	x=554515	y=4442895
Ⅳ	x=552240	y=4442895

The connecting lines of these points constitute the protection boundaries which is based upon the area of the maintaining zone designated by the Designing Institute of Coal Mining, achieving by calculating the extension to a depth of 300 meter with a ground projection, considering a sinking exterior angle of 70 degrees.

Geological Information of the Area around Yungang Grottoes

Yungang Grottoes are situated on the northeast boundary of the Da Tong – Jing Le Basin. The Grottoes are mainly located on the west wing of the Yungang synclinal axis. The whole area has a mild slope of five degree. Within the grotto area from NE25° to 35°, no fault was found, while four groups of crannies were developed. (NE60°, SE95°,SE117°,NW50°) According to the information collected by underground mining, the crannies at the lower stratum are also developed, and function as the main channels of groundwater.

According to the information collected at the Yungang No.1 mine, the stratums, from bottom to top are 200 meters of Cambrian and Ordovician stratum, 40 meters of cornbrash shale and clay pan, 110 meters of Jurassic sandstone and arenaceous shale. This stratum includes 13 layers of coal seven of which are minable with a thickness of 14 meters. Among these layers, the upper No.2 layer is the main coal layer that has a thickness of 4.4 meters. The top stratum at the No.1 mine is the Jurassic stratum mainly formed by sandstone with interlayers of argillaceous shale. The upper layer of this stratum is a thick sandstone layer with sporadic thin layer of purple and gray argillaceous shale. This stratum of sandstone has a wide area of outcrops that includes the grotto area. The sandstone with micaceous feldspar quartz is easily subject to weathering, which becomes one of the main factors of grotto collapses and damages.

Sectional Layout and Observation Instruments

1 Sectional Layout(Please refer to the Working Layout with a scale of 1:5000)

1-1 Moble Observation

Centering at the No.13 Grotto, Sections of the ground quarry and the underground mining explosion points were made:

1-1-1 Section I is from No.13 Grotto to the Qing Ci Yao Mine. It has a length of 2,750 m. There are four observation points starting from the explosion point. The observation was carried out twice. The doses of explosive powder are 3.0 kg and 1.8 kg respectively.

1-1-2 Section II is from No.13 Grotto to the quarry of the Yungang Main Mine. It has a length of 875 m. There are four observation points along the section. The dose of explosive powder is 1.8kg.

1-1-3 From No.13 Grotto to the explosion point of the Yungang Main Mine is the III Section the length of which is 1,295m. There are three observation points. The observation was carried out twice. The doses of explosive powder are 3.15 kg and 3.0 kg respectively.

1-1-4 From No.13 Grotto to the explosion point of No.8103 Tunnel is the IV Section the length of which is 1,100m. There are four observation points along the section. The dose of explosive powder is 3.0kg.

1-1-5 Section V is from No.13 Grotto to the quarry of Yungang Brigade. It has a length of 1,050 m. There are four observation points along the section in the opposite direction to the Grotto. The observation was carried out three times. The doses of explosive powder are 9 kg, 15 kg and 21 kg respectively.

1-1-6 Section VI is from No.13 Grotto to the explosion point of No.218 Tunnel of the Wu Guan Tun Mine, with a length of 1,446m. There are four observation points along the section. The observation was carried out twice and the dose of explosive powder is 3.7kg for both times.

1-1-7 Section VII is from No.13 Grotto to the explosion point of the Pump Room Tunnel of the Wu Guan Tun Mine, with a length of 1,540m. There are four observation points along the section. The observation was carried out twice and the dose of explosive powder is 3.76kg for both times.

1-2 Fixed Point Observation

Observations were carried out with the measurement instruments fixed in grottos, while trains and trucks running at maximal speed and with maximal load within the normal range.

1-2-1 Train Vibration Observation Seven observation points were set up along the section of 7,000m. Point No.1 is the No.2 Mine of Hong Jiu Mine and Point No.7 is 500 meters south of the Wu Guan Tun Village.

The uptrain departed at 00:12 at a speed of 50km/h with

52 carriages. The whole body of the train is 634 meters long. The total weight is 1,220 t (locomotive 220 t, carriages 1000 t).

The downtrain departed at 06:46 at a speed of 50km/h with 59 carriages. The whole body of the train is 722.5 meters long. The total weight is 4,255 t(locomotive 300 t, carriages 3955 t).

1-2-2 Truck and Tractor Vibration Observation From the No.1 observation point at Gong Ren Village Highway Bridge to the Wu Guan Tun Coal Mine, there are totally eight observation points. Observations were carried out twice both for the truck and the tractor. The total weight of the truck is 13 t with a carrying capacity of 7 t and a self-weight of 6 t. The total weight of the tractor is 7 t with a carrying capacity of 4 t and a self-weight of 3 t. The observation time was from 20:00 to 22:00 with a truck speed of 40-50km/h and a tractor speed of 20km/h.

1-2-3 According to the requirement that the micro-vibration oscillator has to be placed at the basic terrane, the Section I was changed from original SE 16.5° to NW50° while The Section II from SE 10° to NW83°. The observation points of the V Section were placed along the section and in the opposite direction of the grottoes.

The alteration above was made supposing a homogeneous medium condition within the Yungang Area which does not have considerable changes, as well as meeting the needs of practical working conditions.

Results Calculations and Analyses

1 Testing Conditions:

1-1 The stratum of the whole area is alternative Jurassic sandstone and shale. The obliquity is 5° and the slope is mild. There is no fault found in the area. The level difference of the explosion points is about 200 meter.

1-2 Tests were made with explosive powder doses which are within the normal range of practical production. The only exception is for Section V where the dose of 21kg is above the normal range for practical production in that area.

1-3 39 point/time observation was carried out in the seven sections of the explosion points. There are seven observation points for the railway and eight for the highway. 54 point/time observation were carried out in the whole area, among which 31 point/time were sampled for the calculation.

Illustration 1: Copy of the 16-line Wave Indicator Records made on April 14 at the Yungang Brigade with a Dose of 21kg

Illustration 2: Records of the Underground Mining Explosion at the Section III on April 19 with a Distance of 325m and a Dose of 3.15kg

Illustration 3: Records of the Underground Mining Explosion at the Section I on May 4 with a Distance of 490m and a Dose of 1.8kg

Illustration 4: Records of Train Observation on April 17 with a Train Weight of 4225 t

Illustration 5: Records of the Ground Explosion at the Yungang No.1 Mine with a Distance of 480m and a Dose of 1.8kg

1-4 A Distance within the range of 150-1500m from the observation point to the explosion point was adopted according to the transmission bands range of the 1-20HZ indicator as well as the regularity that the seismic wave attenuates along with the increase of the distance. (Appendix III: Table of the Frequencies Attenuations)

2 The Calculation of the Physical Displacements, Speeds and Accelerations that Destroy Architectural Structures

According to the forms of the seismic waves induced by the explosion, the displacements, the speeds and the accelerations have the following relation:

$X = A\cos(\omega t + \phi_o)$

$V = \omega A\cos(\omega t + \phi_o + \pi/2)$

$a = \omega^2 A\cos(\omega t + \phi_o + \pi)$

In the formulae, ω stands for vibration frequency of the particle, $\omega = 2\pi f$, A stands for the maximum swing, x stands for the ground displacement, v stands for the vibration speed of the particle and α stands for the vibration acceleration of the particle.

Because we adopted *f* as the vibration frequency in order to get the displacements, speeds and accelerations, the formulae above could be simplified as:

$X = A$

$V = 2\pi f A$

$A=(2\pi f)^2 A$

The results of calculations are shown in Table II (please refer to Appendix II)

3 The Regularity of the Attenuation of Displacements, Speeds and Accelerations

Many factors can affect the regularity of the attenuation in the explosive vibration, such as the dose, distance from the explosion point, characters of the medium as well as explosive methods. Nevertheless, in the Yun Gan area where the medium is homogeneous, the dose and the distance from the explosion point become the two main factors. Hence, following formulae were developed showing the practical relations among displacements, speeds, accelerations, doses and the distances from the explosion point.

$A\mu=K(\Theta^{\beta}/P)^{\alpha}$

$V(cm/s)=K(Q^{\beta}/P)^{\alpha}$

$\alpha(\zeta)=K(Q^{\beta}/P)^{\alpha}$

In the formulae, stand for dose of explosive powder (kg), R stands for the distance form the observation point to the explosion point (m), K stands for the coefficients with explosive methods and conditions, stands for the index of attenuation.

Results of the calculations:

$A(\mu)=1340(\Theta^{\beta}/P)^{1.56}$ (please refer to Appendix IV)

$V(cm/s)=310(Q^{\beta}R)^{2.19}$ (please refer to Appendix V)

$\alpha(g)=610(Q^{\beta}R)^{2.79}$ (please refer to Appendix VI)

4 Application of the Calculated Results

As distance (R)

increase the attenuation curves of speeds (v), accelerations (α) at different doses were drawn with an allowance of a slight broadening of the practical dose range from 1.8 to 21kg in the Yungang Area. (Please refer to Appendix 7 and Appendix 8.) In the tables in Appendix 7 and 8, the values of speed and acceleration can be obtained through the calculation with the known values of the explosive dose and the distance from the explosion point. The safety radius around the explosion point can be obtained if the minimal damaging values of speeds and accelerations in the Yungang area are provided.The values of ground vibration induced by explosions in several sections around Yungang Grottoes are shown in the following table:

5 Vibration Effects Upon the Grottoes Induced by Other Vibrative Sources

5-1 According to the results collected through texts with trains, vacant trucks and loaded trucks, the vibrations of loaded trucks are greater than those of vacant ones while the greatest vibration is induced by truck groups. The values obtained at the testing points nearest to and fairly far from the grottoes are shown in the following table:

Because the vibrations induced by trucks are around 50HZ that are beyond the testing frequency range of employed instruments, the above values of trucks are just for reference.

5-2 Vibration Effects Upon the Grottoes Induced by Mine Collapses:

One tromometer was employed for the surveillance of natural seismic movements and the vibrative effects in the collapsing areas around different explosion points. 1,700 collapses were recorded within the period shorter than one month, along with different distances and different degrees. The values obtained during two major collapses are shown in the following tables:

According to the data provided by Da Tong Seismological Bureau, the two major collapses in the recent years, the one on March 28, 1972 and the one on June 14, 1973 are equal to earthquakes with ML of 3.6 and ML of 4.0 respectively. The energy produced by them is equal to that by an explosion with 16,000t powder. Moreover, collapses may happen in the exhausted mined area near the boundaries of the protection zone, therefore produce greater damaging energies than normal mining explosions, as well as truck and train movements. With a high frequency, collapses become a major damaging factor to the Yungang Grottoes.

6 Several Notes and Suggestions for Reference:

During the explosions, the vibrative speed value of the seismic wave was adopted as the main index in judgement of the damages to the architectural structures. As generally accepted, when speed (v) = 10 cm/s, the structures begin to be damaged. According to this theory, following notes and suggestions are made:

6-1 Calculation of the Safety Radius:

Different safety radius for different explosion doses were obtained according to the attenuation curve of the seismic wave speed value to the distance, shown as follows:

6-2 More than 1,700 collapses were recorded form April 5 to 29. The values of the fairly great one happened on April 16 as well as the maximum values on other occasions are compared and shown in the following table:

In mine collapses, V (0.00174cm/s), is three times that in mine explosions (0.00048cm/s), and 19 times that in train tests (0.0000925cm/s). Although the distances to the grottoes in mine collapses are much greater than those mine explosions and train movements, the vibrative effects of the former are still greater than the latter two forms. Moreover,

the tested value of ML(1.0) is much smaller than those happened on March 28,1972 (ML=3.6) and June 14, 1973 (ML=4.0). Therefore, mine collapse is one of the major damaging factors to the grottoes. (Illustration 6 Mine Collapse on April 16, 2km; Illustration 7 Mine Collapse on April 13, 15km)

6-3 The Comparison between the Vibration Speed Values of Trains, Trucks, Mine Collapses and V=10cm/s the values of Damaging Sinking for Architectural Structures, shown as follows:

According to the comparisons above, the vibrations induced by train and truck movements cause no damage to the grottoes.

6-4 As analyzed above, the greatest damages from surrounding vibrations to the structures in Yungang Grottoes come from mine collapses. According to the records in the recent year, the greatest collapse has had a vibration value of 4.0 (ML). Nevertheless, the certain rational relationship between the collapses and the effect to structures is still unknown. Furthermore, the damage of mine collapses to the ground is much lighter than that of an explosion with equal energy. Because the force of a collapse is downward, simple reckoning and analogism can not be made basing upon the values of explosion. Therefore, more data should be collected while the damages from mine collapses should be paid much attention to.

Abstract

World Cultural Heritage Datong Yungan Grottoes excavated from easily weathered rock layers since 5 century AD with quality coal bed underground is situated in an area of 57.4 square kilometers around Wuzhoushan. Under the northern geographical and climate conditions, coal mining has been the major way to bring local habitants economic benefits. 16 mining zones distributed surrounding the site had their tunnels gradually approaching to the underground support of the property. Managing organ has estimated the tremors caused by underground mining, quarrying, trains and motor vehicles by using single-direction tromometry, and confirmed that Large-scale collapse of the exhausted mining areas had become the most hazards on the site that possibly lead to destructive human-caused disasters.

The author proposed and will introduce with this paper a technical protection measure as delimiting a hopper-shaped tridimensional security zone of 300-meter depth underground, so called security pillar, which goes top down along the boundary of key distribution area taking the natural rock collapse angle of 70 ° , while the bottom boundary extends with the downward expansion of the mining operation..

The technique has been proved efficient during 30 years of practice. It provided a security model for the conservation of heritage in similar situation.

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Explosion Point	Q	R(m)	V(cm/s)	(cm/s2)	Notes
Qing Ci Yao Mine	3.0 kg	2750	0.000015	0.00042	
8806	3.0 kg	1295	0.000083	0.0035	
Yungang No.1 Quarry	5.0kg	690	0.00048	0.032	
Wu Guan Tun Mine	3.0 kg	1445	0.000064	0.0031	
Quarry of the Yungang Brigade	10 kg	1050	0.00031	0.019	

Type of Vehicle	Weight of Vehicle (t)	No. of Testing points	Distance(M)	Aμ	v(χμ/second)	α(cm/second)^2
Train	4225.0	2	2135	0.0147	0.0000471	0.00148
Train	4225.0	5	630	0.0272	0.0000925	0.0316
Truck group		1	1390	0.002	0.000062	0.0126
Truck group		4	140	0.03	0.00093	0.189

Time	Aμf	ς (χμ/second)	α(cm/ second)^2	Notes
74.4.16	1.38	0.00174	0.0218	
74.4.16	0.69	0.00108	0.017	

dose （kg)	3.0	5.0	10.0	20.0	Notes
Safety Radius	6.3	7.2	9.0	11.5	Unit: m

Type	Aμf	ς (χμ/s)	α(cm/ s)^2	Notes
Mine Collapses	1.38	0.00174	0.0218	
Mine explosions	0.1136	0.00048	0.032	5 kg 690m
Train	0.0272	0.0000925	0.0032	

Type	ς (χμ/s)	Damaging Sinking of Architectural Structures	Percentage	Notes
Mine Collapses	0.00174	10 cm/s	0.0174%	
Mine Explosions	0.00048	10 cm/s	0.0048%	5 kg 690m
Train	0.0000925	10 cm/s	0.000925%	

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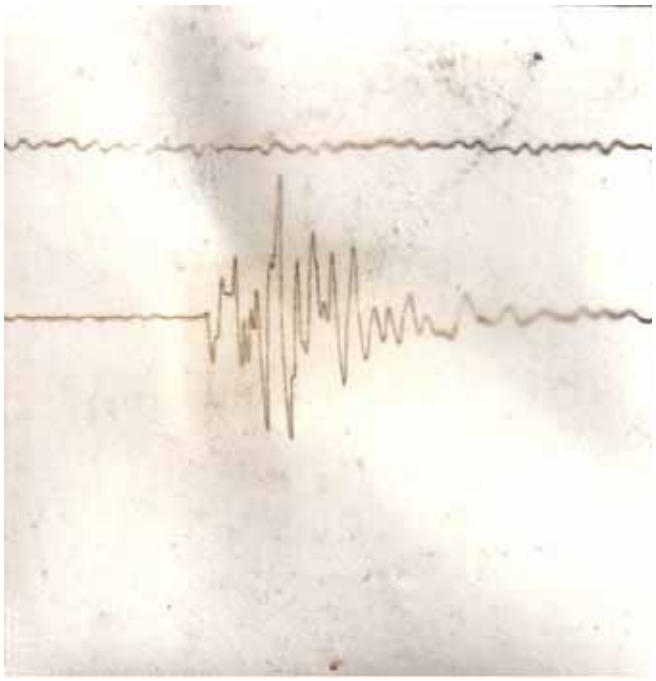

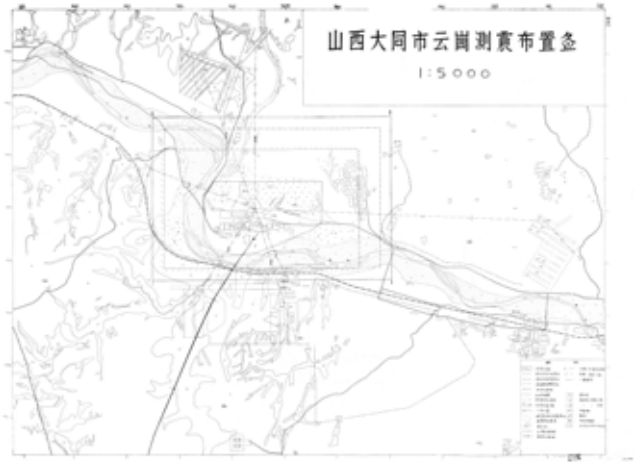

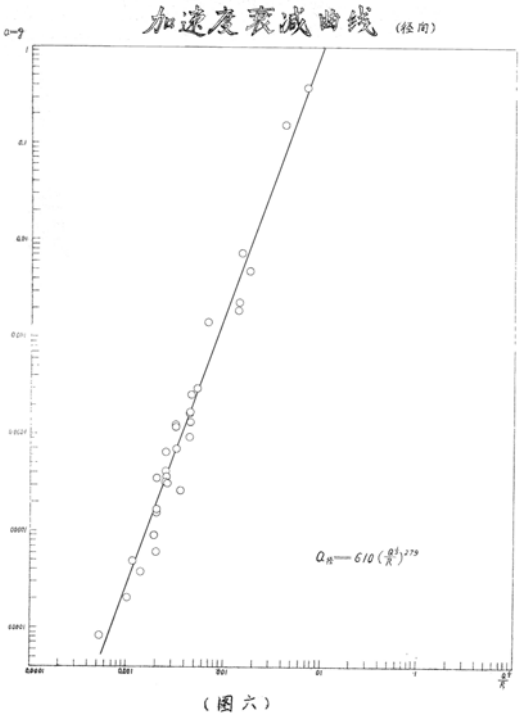

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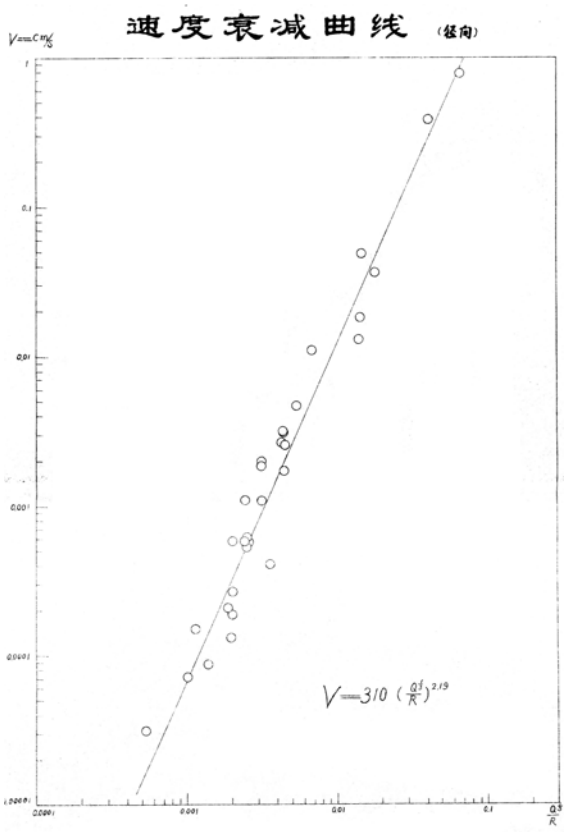

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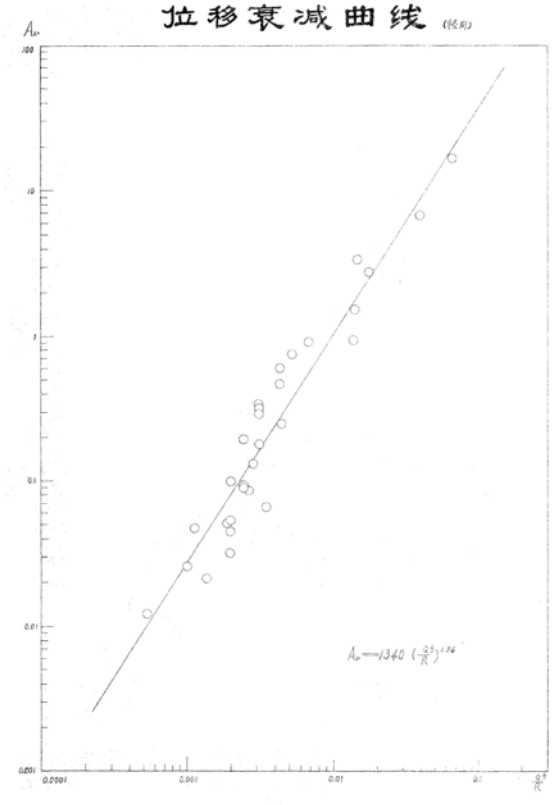

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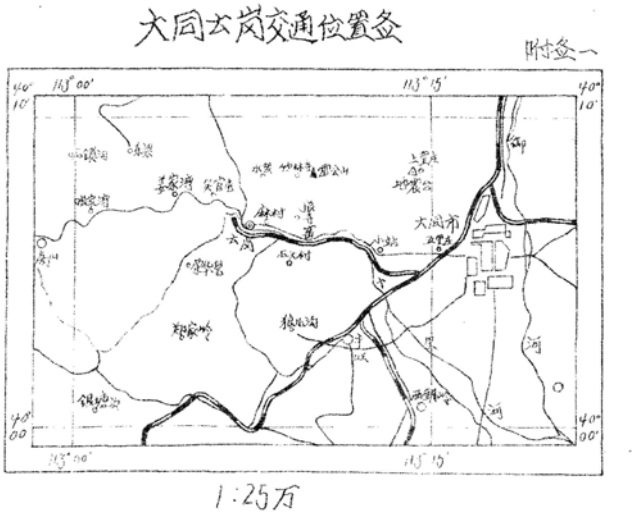
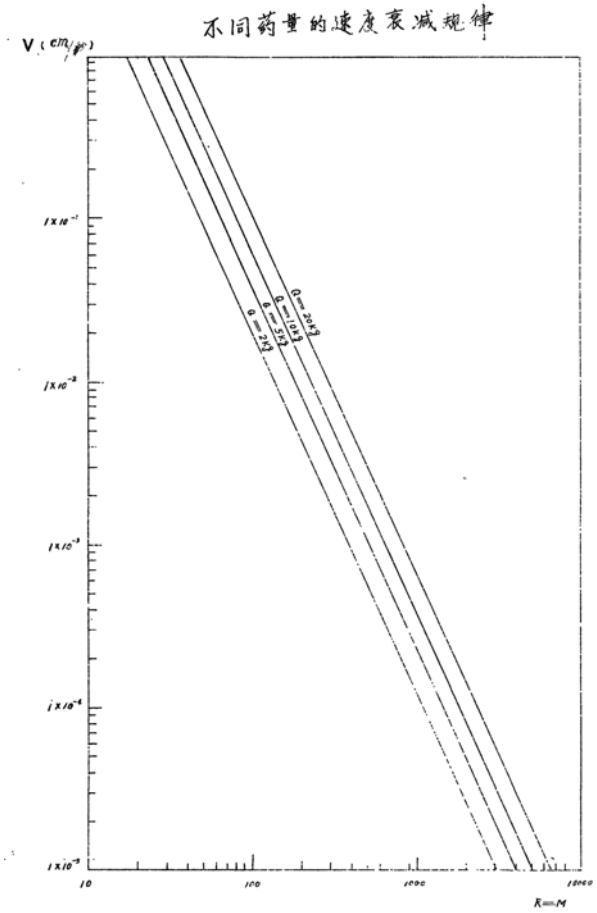


附表一

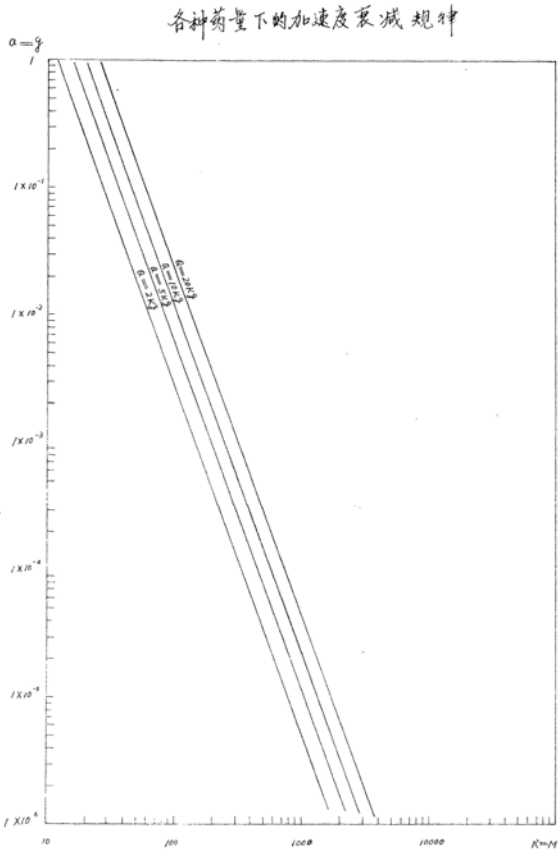
类别	剖面长度(米)	方位(度)	爆破震源 X	爆破震源 Y	药量 第一响	药量 第二响	爆破参数	爆破参数	爆破参数测点 水平距(米)	爆破参数测点 高程差(米)	测点高程(米)	备注
I	2120	SE165°	4441400	333710	3.0	3.0	340.11	1158.7	0—1点	13	1121.45	① I剖面由SE165°改成NW10°。
									0—2点	433	1114.3	
									0—3点	784	1143.3	
									0—4点	891	1134.7	
II	(872) 870	NW15°	4441335	333483	1.8			1146	0—1点	14	1144	② II剖面由SE18°改成NW15°，剖面全长870米。
									0—2点	431	1134	
									0—3点	820	1137	
									0—4点	873	1130	
III	1270	NE18°	4441280	333570	3.15	3.0	339.431	1156.00	0—1点	45.0	1141	③ III剖面爆测点布置在剖面的反方向。
									0—2点	903	1135	
									0—3点	1197.0	1143	
IV	1100											1144.5至1126.2点不详
V	(189) 1100	NW45°			4.0				0—1点	41		④ 仪器距爆源距离，爆剖面投影长度。
									0—2点	88		
									0—3点	116		
									0—4点	137		⑤ 空前点与最高点不大对应的剖面不取。
VI	1443	SE215°	4441318	332370	3.75	3.75	1031	1173	0—1点	121	1115	
									0—2点	403	1114.4	
									0—3点	764	1143.3	
									0—4点	973	1134.1	
VII	1342	NE3°	4443541	333421	3.75	3.75	1102	1162	0—1点	201	1150	
									0—2点	512	1151.4	
									0—3点	927	1152.4	
									0—4点	1213	1152.5	
补 I	360	NW130°	4441463	333710	1.8	1.8	341.11	1158.7	0—1点	13.4	1151.3	
									0—2点	247	1151.4	
									0—3点	496	1147.5	
									0—4点	756	1141	

附表二

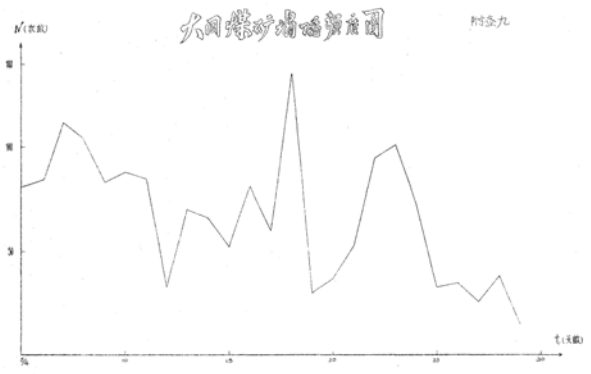
剖面	日期	Q (KG)	R (M)	Am	V (Cm/秒)	a (Cm/秒²)	f (Hz)	备註
III	4.19	3.15	1225	0.250	0.00255	0.260	62	Q 药量
	4.19	3.00	1295	0.041	0.000151	0.0068	5.1	Am 地动位移
V	4.14	21	41	16.700	0.7800	373.0		V 振动速度
	4.14	21	68	16.700	0.3180	152.0		a 振动加速度
	4.19	21	136	2.730	0.0283	4.778	21	f 位移频率
	4.18	21	189	1.333	0.0091	2.260	23.5	R 观测仪器距爆心距离
	4.18	21	1070	0.127	0.00132	0.0302	7.7	
I	5.4	1.8	216	0.270	0.049	0.1704	8.5	
	5.4	1.8	387	0.087	0.00183	0.1170	10.2	
	5.4	1.8	490	0.188	0.0011	0.0640	9.3	
	5.4	18	608	0.0978	0.00078	0.348	9.5	
II	4.30	1.8	360	0.065	0.00061	0.0256	10	
	4.30	1.8	480	0.083	0.00057	0.0464	11	
	4.30	1.8	645	0.05	0.00021	0.0089	6.7	
	4.30	1.8	875	0.021	0.000098	0.0071	6.7	

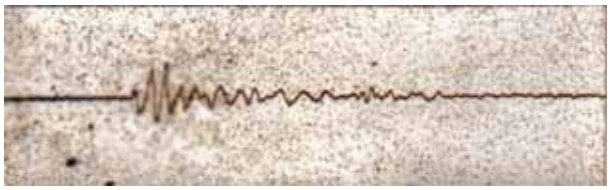

不同药量的速度衰减规律
V (cm/s)
Q=20kg
Q=10kg
Q=5kg
Q=2kg
10
100
1000
10000
R=M

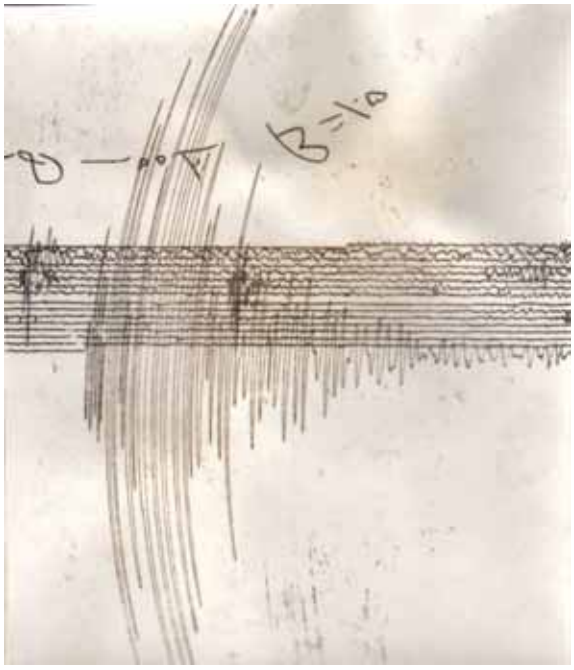
（图七）

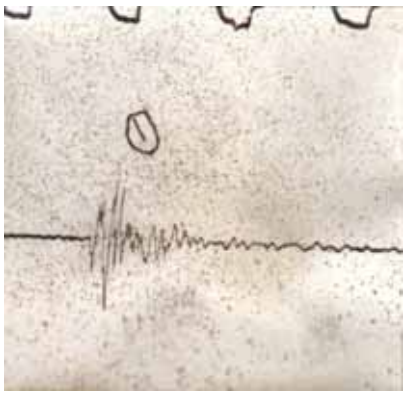

各种药量下的加速度衰减规律
a=g
Q=20kg
Q=10kg
Q=5kg
Q=2kg
10
100
1000
10000
R=M

（图八）


大同煤矿塌陷资质图
附图九







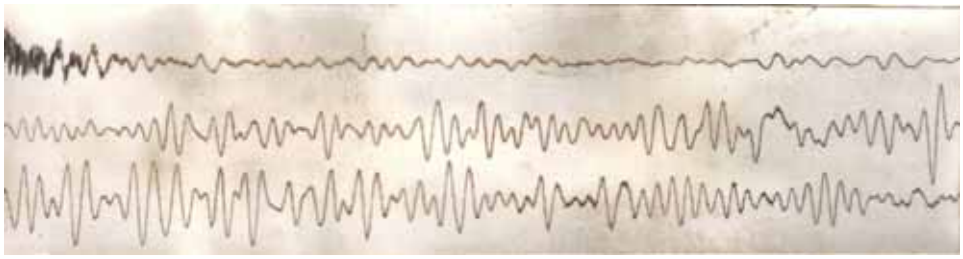


Figure 1. Map showing the location of Yungang Grottoes in Datong , 1:250,000
Figure 2. Vibration Measurement Working Layout at Yungang Grottoes in Datong, Shanxi, 1/5000
Figure 3. Chart of attenuation of frequency along with the increase of distance from the explosion point
Figure 4. Chart of attenuation of displacement along with the increase of distance from the explosion point
Figure 5. Chart of attenuation of speed along with the increase of distance from the explosion point
Figure 6. Chart of attenuation of acceleration along with the increase of distance from the explosion point
Figure 7. Chart of attenuation of speed caused by different explosive powder doses
Figure 8. Chart of attenuation of acceleration caused by different explosive powder doses
Figure 9. Chart of frequency of mine collapses