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# Gravity Prospecting of Underground Palace of Ming Tombs, China

Hao, Tianyao*, Wang, Qianshen* and Suh, Mancheol**
*Institute of Geology and Geophysics, Chinese Academy of Science
**Nondestructive Research Lab. of Cultural Property, Kongju National University

**Abstract**

Microgravimetry is a rising and important branch developed on the foundation of classical gravimetry. In this paper, methods, techniques and application of microgravimetry for underground Palace are introduced. Some survey curves show agreeable result compared with the theoretical calculation of models. It can be a useful method for looking for underground palace and catacombs.

**Key words:** Microgravimetry, gravimetry, survey curve, underground palace, catacombs

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**요약:** 미세중력 측정기는 최근 그 중요성이 부각되고 있는 분야로 전통적인 중력측정장치를 기초로 개발되었다. 이 논문에서는 지하 궁전 탐사 작업을 위한 미세중력 측정기의 원리와 기술, 그리고 활용법을 소개한다. 몇몇 조사 곡선들은 모델들을 통한 이론적 계산치와 비교하여 볼 때 꽤 만족스러운 결과들을 보여주고 있다. 이 방법들은 지하의 왕궁이나 묘지들을 탐사하는데 유용하게 사용될 수 있을 것이다.

**주요어:** 미세중력측정기, 중력측정장치, 조사 곡선, 지하 궁전, 묘지

*(Hao, Tianyao and Wang, Qianshen, Institute of geology and geophysics, Chinese Academy of Science, Beijing, 100101, People's Republic of China; Mancheol Suh, Nondestructive Research Lab. of Cultural Property, Kongju National University, Kongju, Chungnam 314-701, Korea. email: mcsuh@kongju.ac.kr)*

## 1. Introduction

A survey of the outline, location and buried depth of catacombs was carried out by Institute of Geophysics, Chinese Academy of Science, with mircogravity method and vertical gravity(VG) survey as regard to Mao Ling mausoleum(tomb of Zhu Youcheng). Before the operation, an option of Ding Ling mausoleum(tomb of Zhu Yijun) which was already excavated was taken as known object to be the first surveyed. Microgracity and VG survey were carried out at Ding Ling mausoleum, in order to verify the designing plan to find out the correlation between data observed and the actual parameters about size, outline, location and buried depth etc. of the subsurface object. Thereafter, the project design, the survey area, and the method of survey to be taken place at the unknown Mao Ling mausoleum were determined upon experiences secured at the known Ding Ling mausoleum.

In order to compare the result that we got in Mao Ling and other tombs, we calculated some models of underground palaces and got the gravity curves of them. We get the calculation result of whole these models and believe that they are useful comparing with the actual survey curves during the job looking for the underground palace in further.

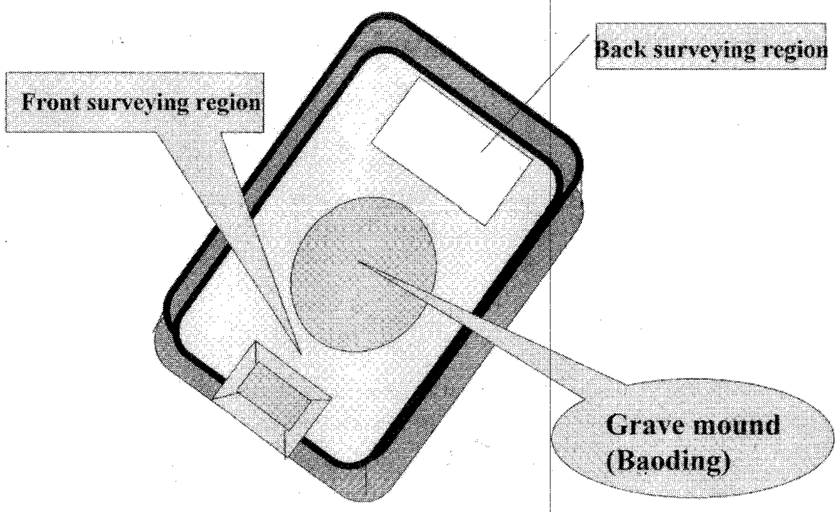



**Fig. 1.** Outlook of Mao Ling mausolem of Ming Dynasty.

## 2. Exterior figure of Mao Ling mausoleum and lay-out of survey region

The general layout of buildings of Mao Ling mausoleum and Ding Ling mausoleum are quite similar in exterior outline(Fig. 1). Each comprises a gateway hall(Ming Lou), a grave mound(Bao Ding) and a surrounding wall. The construction pattern of the underground palace of Ding Ling mausoleum is already known from excavation. The main hall is located at the back of "Bao Ding" and the entrance is in front of it. As based on such constructional pattern, the back survey region with an area of 30 m x 50 m was designed behind the grave mound. A front survey region was laid out at the central and front parts. A number of longitudinal profiles and several traverse profiles(front survey region) perpendicular to the longitudinal profiles were designed to connect the front and back regions. The distance is 3 m between profiles as well as between stations(Fig. 2). Every station was pegged and their locations and altitudes were all determined and surveyed to tie-in a datum point in the gate hall.

Such datum point is by no means to tie-in with the geodesic coordinate and the absolute altitude station (benchmark). The central part of the cemetery is a grave mound, called "sacred top"(Bao Ding). The brick wall closely surrounds the cemetery with 3 m thickness and 6 m height. Building correction due to the wall and terrain correction due to the grave mound is necessary in data processing.

## 3. Microgravity survey

Microgravity survey was enforced according to the way and notification described in the past paper. The height from each peg to the bottom of gravimeter is determined in situ. Survey was taken by a pair of L-R gravimeters, each with an accuracy less than 5 $\mu$Gal. Accuracy of level survey was 1 cm. Latitude correction was applied although the distance between stations at both ends of NS profile in back region was only 30 m.

Data processing was done according to the way described in Section 5. After correction and calibration., a map of gravity anomaly was made(Fig. 3).

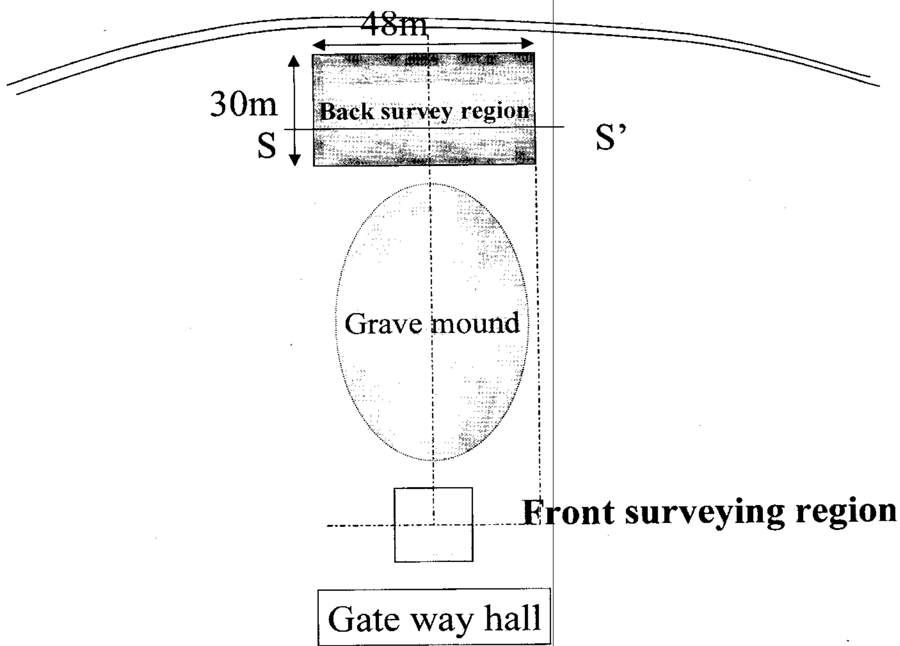



**Fig. 2.** The Microgavimetry network spread of Mao Ling.

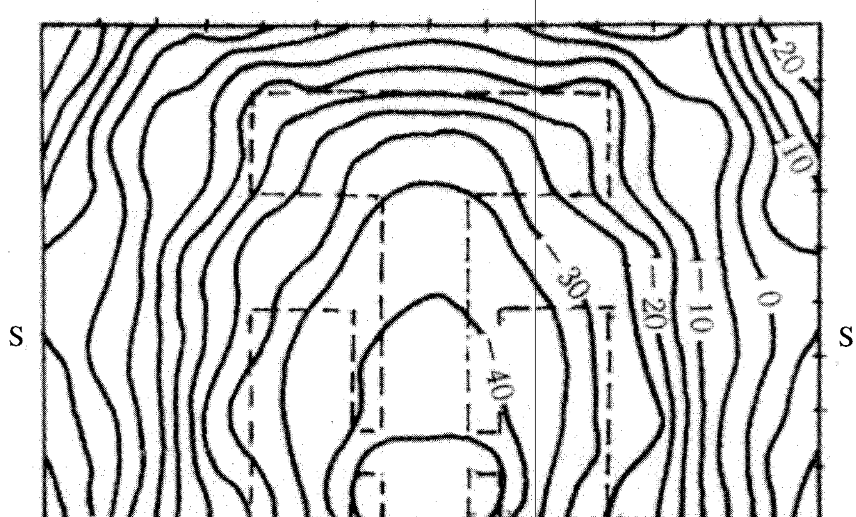



**Fig. 3.** The gravity anomalies of back survey region of Mao Ling mausoleum.

## 4. Shallow seismic prospecting

Profiles of shallow seismic prospecting were laid out in both back and front regions in order to ensure better accuracy and reliable interpretation. The profile is shown as S-S' in Fig. 2, which was carried out by hammer seismograph. Distance between stations was 3 m. From the seismogram, it appears that a layer of substance with highspeed equivalent to the speed of limestone was located at the depth of 13 m. It shows that there should be a roof of limestone at the very depth that is close to the result of gravity anomaly interpretation(12 m).

## 5. Forward computation of gravity anomaly

As based on the surveyed seismogram and the distribution of gravity anomalies, a primary model with its three dimension geometrical parameters of the underground was established(klaus · Vestergaard, 1991; Dobroka *et al*, 1991; Laszlo *et al*, 1994).

Palace of Mao Ling mausoleum was given by reference of known structure of Ding Ling mausoleum, and traditional symmetric layout of ancient Chinese palace and catacombs of emperor. Through forward computation of multiple approaching approximation, an optimal result was agreed with the gravity anomaly practically surveyed(Fig. 4). On grounds of which, the parameters concerning location of Mao Ling mausoleum catacomb(the underground palace) and a plan view as well as a stereoscopic drawing was given as shown in Fig. 5a and Fig. 5b.

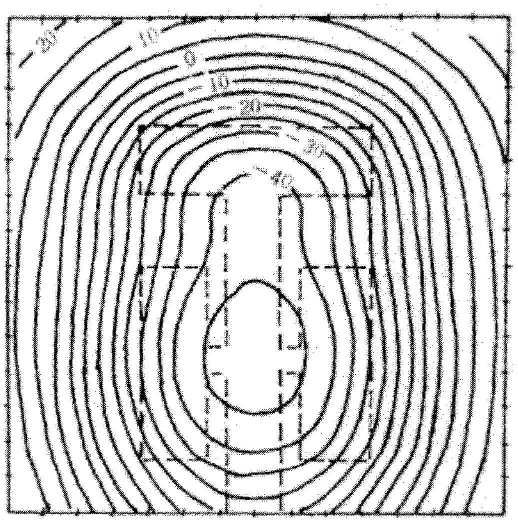


**Fig. 4.** Gravity anomalies of model of back survey region of Mao Ling mausoleum from forward computation.

The value of density is assumed to be 2.0 g/cm$^3$ for the upper overburden, 2.2 g/cm$^3$ for the lower overburden, 0 g/cm$^3$ for the vacant space of tomb, and 2.6 g/cm$^3$ for the limestone roof, wall and floor surrounded. From Fig. 4, it can be seen that the shapes of gravity anomaly obtained from forward computation of a model(Rasmussen · Pedersen, 1979; Enmark, 1981) and from the practical observation are basically agreeable, but with a difference of numerical value between them. The reasons maybe:

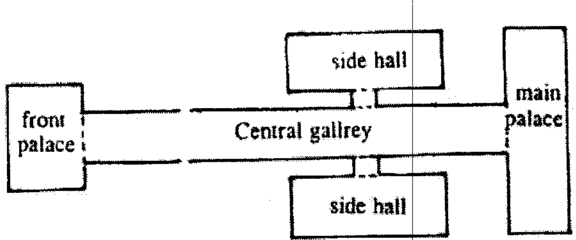
(1) The subsurface structure of the Mausoleum is unknown, and the present model is merely conjectured against the excavated Ding Ling mausoleum and other historical materials, so that certain discrepancy between the model and the actual one was unavoidable.

(2) Density of topsoil was determined by sampling, while the natural deep-buried soil and the true thickness of overburden and its density after the construction of mausoleum are not so clear, so that they may confuse the model computation.

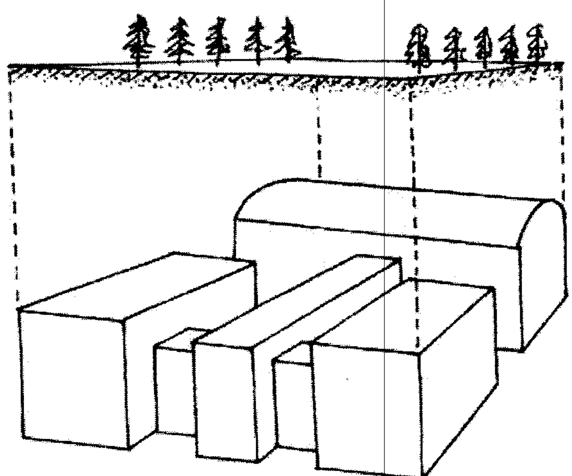
(3) Model simulated is too simplified(six vacant spaces adopted for the model). The thickness of the masonry lining structure is supposed to be uniform, while the possible thickening or thinning is not considered.

(4) Dissociation of regional anomaly and extraction of residual anomaly are not quite pure.

Therefore, microgravimetry is available and effective for catacomb prospecting. Of course the model design must be approximated through multiple adjustment, and the density data must be determined




(a)



(b)

**Fig. 5.** (a) Plan view of Mao Ling catacomb; (b) Stereo drawing of Mao Ling catacomb.

reasonably by detail sampling in order to minimize the error as rare as possible. Moreover, VG survey could be applied in supplementary and checking when necessary.

## 6. VG survey

Mao Ling mausoleum is an unexcavated catacomb, so its exact construction style is not very clear. During the microgravity survey, calculation and study of some ideal model were taken. The result obtained coincided basically with the data actually observed. But there are still discrepancies in numerical values. VG survey was operated by using LaCoste & Romberg (L-R) type gravimeter which is characterized by this high precision and slight zero drift. The cradle was a tripod 1m high with an adjustable metal supporting plate(to support the gravimeter). A round of three readings was taken successively at low, high, and low altitudes again. After solid-tide correction, an average of each pair of gravity difference was calculated and then divided by the vertical distance to obtain VG values.

### 6.1. Model and computation

On the assumption that the front region is

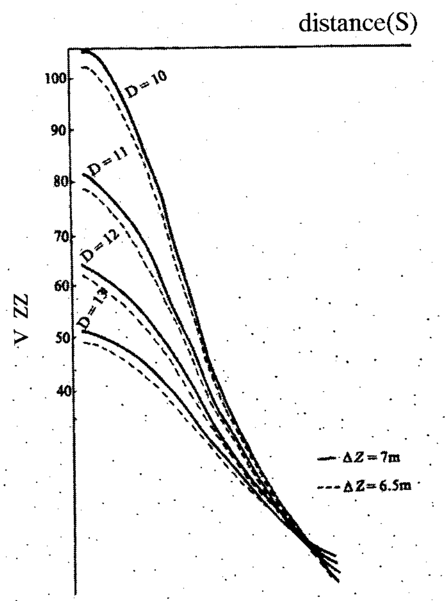



**Fig. 6.** Distribution of VG from cubes with different size and bury depth D; bury depth(m) of the top of cube; delta z: Height(m) of the cube.

corresponding to that of the Ding Ling, front hall is assumed to be a three-dimension cube(Fig. 6a). Values of theoretical VG along the profile were produced by cube and an interpretation was made by comparison of VG between the computed and the actually observed along the same profile. This profile was laid along the central axis of the assumed front hall.

Profile of VG was also laid in back region as a line assumed running across both side halls and the central gallery. It is also the profile of seismic prospecting as well as microgravimetry so as to be a profile of comprehensive interpretation. Model of back region comprises 4 cubes(the main hall, side halls on both sides and a central gallery). Similarly, VG of four cubes were computed separately and overlapped to obtain respective general VG of each cubed and further obtain the theoretical value of VG along the whole profile. The theoretical VG was computed with the surveyed one to be analyzed and interpreted afterwards. The calculation formula of VG of a three-dimension cube is expressed as follows:

$$\begin{aligned}\nu_{zz} = & -66.7\times10^{-11}\times \\ & \rho\left\{\left[tg^{-1}\frac{x_2y_2}{z_2\sqrt{x_2^2+y_2^2+z_2^2}} - tg^{-1}\frac{x_1y_2}{z_2\sqrt{x_1^2+y_2^2+z_2^2}}\right]\right. \\ & -\left[tg^{-1}\frac{x_2y_1}{z_2\sqrt{x_2^2+y_1^2+z_2^2}} - tg^{-1}\frac{x_1y_1}{z_2\sqrt{x_1^2+y_1^2+z_2^2}}\right] \\ & -\left[tg^{-1}\frac{x_2y_2}{z_1\sqrt{x_2^2+y_1^2+z_1^2}} - tg^{-1}\frac{x_1y_2}{z_1\sqrt{x_1^2+y_2^2+z_1^2}}\right] \\ & \left.-\left[tg^{-1}\frac{x_2y_1}{z_1\sqrt{x_2^2+y_1^2+z_1^2}} - tg^{-1}\frac{x_1y_1}{z_1\sqrt{x_1^2+y_1^2+z_1^2}}\right]\right\} \quad (1)\end{aligned}$$

In which, $X_i$, $Y_i$, and $Z_k$(I, j, k=1 or 2) are the coordinates of vertices of cubes.

The curves of VG anomaly are calculated against cubes with different size and different buried depth at different place on ground. The maximum VG produced of any object at a certain depth can be determined or estimated conveniently from the curves in fieldwork.

From Fig. 6, it is shown that VG varies sharper with large size and shallower depth of the object. Two curves of the distribution of theoretical VG

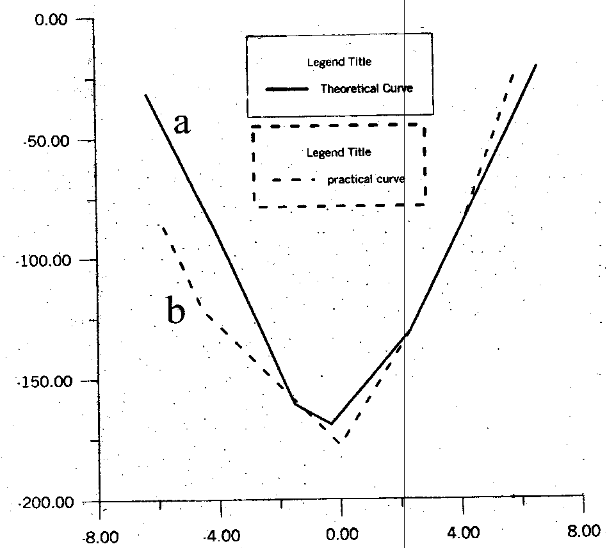



**Fig. 7.** A comparison between computational VG curve and practically surveyed curve (a) Theoretical VG curve; (b) Practically surveyed VG curve.

are drawn on the corresponding curves of actually survey VG both in the front and the back region, Mao Ling mausoleum, Dotted line (a) in Fig. 7 is theoretical VG in front region. At left terminal, curve b is lower than that of a, and also lower than the anomaly of right terminal which maybe caused by the vacancy of the gallery and other nearby side hall.

There is no construction at the right end of curve b. So it is fairly agreeable with line a.

The VG anomaly curve in the back region shows that there are three low extreme in both curves. Theoretical values are not so regular and symmetric as observed values. A difference in numerical value also exists between them. This is caused by the uneven distribution of subsurface substantial densities. However, the superiority of the VG anomaly other than gravity anomaly is its higher resolving ability. It is hardly to distinguish the main central hall, side halls and the gallery distinctly from the vagueness. We may disregard the anomalies as a big single hall.

However, they are distinguishable clearly by the VG anomalies across the survey area. This indicates that the anomaly of VG plays an important role in the discrimination of structure pattern of the subsurface mausoleum, and shows its significance and capability in detecting the subsurface structures and patterns.

## 7. Conclusion

Micrgravimetry is a rising and important branch developed on the foundation of classical gravimetry. In this paper, methods, techniques and application of microgravimetry for underground Palace are introduced. Some survey curves show agreeable result compared with the theoretical calculation of models. It can be a useful method for looking for underground palace and catacombs.

Micrgavity method is useful method for looking for catacombs. The result is better specially when we use vertical gravity(VG) survey method. It can be shown that the size, sharp and location of targets underground. The advantage of this kind of method is economical, quick and effective. Especially it is a nondestructive safety method for study of culture heritage in the course of searching.

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