Zhang Heng’s Seismoscope (4): Restoration Research

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In view of the important prestige of Zhang Heng’s seismoscope in world culture, scholars in different countries have performed restoration research; however, so far all restored models have only reached the drawing design and exhibition stage. In recent decades, new research achievements on historical materials, archaeology and historical seismology have been made in Chinese academic society, which lay a good foundation for the establishment of a new restored model. Not only does the new model more accord with historical materials, but it can be used to detect earthquakes for the first time. This paper will introduce the restoration in four aspects: scientific train of thought, structural restoration, formation restoration and scientific testing.

Key words: Scientific restoration; Seismoscope; Scientific experiment

INTRODUCTION

The restoration research on Zhang Heng’s seismoscope involves the restoration of the working principle, structure and artistic formation. Of course, the restored model is not the historical original, but an approximation to some extent which will change with development of materials and research. In this course, we obtain enlightenment, and understand how human civilization advances. This will play an active role in the popularization of science.

1 SCIENTIFIC TRAIN OF THOUGHT FOR RESTORATION RESEARCH

Restoration research on Zhang Heng’s seismoscope has been carried out for more than 100 years with a checkered process. It has gone through three important stages from major results: Hattori and Milne (1883) made the restoration drawing design according to historical materials and deduced the working principle of the suspension pendulum in the 19th century. Wang Zhenduo (1963) turned the restoration drawing into an exhibition model, but believed it was operated by the upright pole in principle in the 20th century. In recent decades, new progress

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from studies on historical materials, archaeology and historical seismology were achieved in the Chinese academic field, which have laid a good foundation for establishment of the new restored model. Not only does the newly-restored model more accord with historical materials, but can also detect earthquakes for the first time. In the model, the suspension pendulum working principle is adopted (Feng Rui et al., 2006).

1.1 Determination of Working Principle

The working principle of the instrument is most critical in the research process, and this will decide its structure and external formation. There are three views to understanding the description stated in the historical material, that is, "In the inner part of this instrument there was a general pillar in the middle, that could move laterally along eight roadbeds". Accordingly, there are three working principles: suspension, the suspension pendulum (Milne, 1883), upright pole (Imamura, 1939) and free pole (Li Zhichao, 1994). Our study shows that the suspension pendulum principle is most in accord with the original meaning of historical records for the reasons as follows:

(1) According to the historical materials "In the inner part of this instrument there was a general pillar in the middle, that could move laterally along eight roadbeds" and "In case an earthquake occurred, the ground movement swayed the jar, the jar would shake accordingly. Following the swing orientation of the jar, the lever released, and the dragon instantly dropped the ball out of its mouth", we draw the following conclusions: At first, the Jar sways when earthquake occurs, while the Pillar doesn't move nor fall down. It only keeps itself suspended and remains practically at rest, with a relative motion together with the jar body. On the other hand, it demonstrates that all parts of the seismoscope are affected in a specific order, i.e., swaying of the jar body—the trigger acting—the lever releasing—dragon spitting out the ball in the direction of the earthquake, which is the special response of the suspension to earthquake. On the contrary, if the general pillar is a simple upright pole, the longitudinal wave causes the movement in a reversed order, i.e., "the lever releases first, then the jar shakes".

(2) Historical literatures also show the response of this seismoscope to the earthquake occurring in the Longxi region at about 600km away, no shaking was felt by people in the location where the seismoscope was set, while the instrument vibrated along the seismic ray. It is reasonable to infer that the functional seismic phase was a Rayleigh surface wave with a period of 2 ~ 10 seconds and an amplitude of 4 ~ 8mm, which appeared more than one minute after the primary wave. It also infers that the seismic intensity is 3 ~ 4 degrees at Luoyang and the acceleration is around 1 gal (Feng Rui and Yu Yanxiang, 2006). Only the suspended structure could detect such extremely weak seismic wave signals, which has been a definite experimental conclusion drawn in early seismology.

(3) Scientific experiment. With strict experiments for three principles set forth in the early studies, the feasibility of the upright pole and free pole used to detect the earthquake is excluded. Theoretical calculation by seismology, historical earthquake comparison, frequency response experiment, simulated experiment for Longxi earthquake, experiment by real seismic records, and strong anti-interference experiments all prove the rationality of the suspended structure.

1.2 Scientific Train of Thought to Establish the Restored Model

The following block diagram shows our scientific train of thought to establish a new restored model. According to historical records, the quantitative or semi-quantitative seismological parameters are proposed, so that the primary model is designed. The model is tested and improved repeatedly with the movement of vibrostand controlled by the computer, and is further examined according to contemporary seismograms. If all this were satisfactory, the model structure
would be accepted.

The scientific train of thoughts of restoration

2 STRUCTURAL RESTORATION

2.1 Basic Form of Structure

It is recorded in historical literatures that "The instrument was cast in fine copper, the diameter of which was eight Han Chi (a Chinese traditional unit of length). In external form it resembled a wine jar with a vaulted lid". In view of the numerous steady wine jars made in the Han Dynasty excavated in the extensive regions, we measured ratios of all parts of the jars to their diameter, such as height of the jar, phoenix, vertical wall and top lid as well as radian of top lid based on 11 pieces of Han jars and their photos (Fig. 1). As a result, the following control parameters of the seismoscope formation were drawn: total height is 3.25 m, the diameter is 1.94 m, total weight is 2.17 tons, and the natural period of the general pillar is 2.92 seconds. The stable bearing intensity of pressure to the foundation is 15 tons per square meter through investigation to the Ling Observatory and analysis on the samples of tamped earth in its foundation. The aforementioned estimated weight of the seismoscope thoroughly satisfied the
allowable load of the Ling Observatory.

Fig. 1
Wine jars made in the Han Dynasty, assuming their own diameter as a “unit”, and measuring their ratios of all parts
(a) Tubular jar; (b) Wine jar; (c) Basic form of the restored model

2. 2 Internal Structure

According to historical records, there are five parts inside of the seismoscope, which are: general pillar, trigger, eight roadbeds, dragon lever, and copper balls.

Fig. 2
Shorter and thicker columns made in the Han Dynasty; the numbers under columns are corresponding ratios of height to diameter

(1) General pillar — The columns made in Han all are shorter and thicker, the ratio of height to diameter ranges from 3 to 5 (Fig. 2);
(2) Trigger — A trigger mechanism, set in the hub where the eight roadbeds gather. See relevant reference (Feng Rui and Wu Yuxia, 2014);
(3) Eight roadbeds — The route leading to small copper ball, with a U-shaped section, and set in eight directions;
(4) Dragon lever — Lever structure;
(5) Copper ball — Copper balls held in the mouth of dragons; once the dragon lever turns and triggers a ball, it will fall to the mouth of a toad.

3 RESTORATION OF FORMATION

The restoration of formation is the need of the instrument in function, and also is an intuitive
way to embody the culture and arts of the Han Dynasty. The formation could also reflect the characteristics of politics and social ethics, as well as aesthetic consciousness of the time. Now some points about the formation are described briefly as follows.

Fig. 3
Stone relief made in the Han Dynasty, where the golden crow carried the sun to fly, and black round dots represent the Big Dipper

3.1 Phoenix on the Top Lid

It is characteristic of bronze ware in ancient China to have a phoenix built on the top of the ware, and it represents all-powerful and imperial sun, indicating sun worship of ancient times (Fig. 3). This kind of formation appeared in the Neolithic Age at the earliest (about 5300 ~ 4200 years up to now). Later, it appeared popularly on bronze wares (Fig. 1 (a), (b)). For this reason, these object formations deservedly appeared on the restored model of seismoscope (Fig. 1 (c)).

Fig. 4
Ornamentations of Four Intelligent Creatures represent four directions of east, south, west and north, as well as four seasons, namely, spring, summer, autumn and winter

3.2 Surface Ornamentations

The historical records definitely indicate the seismoscope “was ornamented with antique seal-characters, and figures of a dragon, turtle, phoenix and unicorn”, which refer to the symbol of
directions in the Han dynasty to decide the direction of an earthquake. Three basic methods were reflected on the wall of the seismoscope. They are the Four Intelligent Creatures, Eight-Divinatory-Trigram seal characters and divinatory symbols, with pragmatic and mysterious qualities. If the phoenix on the top was regarded as the sun, and vaulted lid as the boundless vault of heaven, then the surging Four Souls counterclockwise operated the power of four seasons, and performed the duty of four directions (Fig. 4).

![Fig. 5](image)

Toad in the moon in a famous myth of the Goddess Chang-É’s flying to the moon in a mural in ancient China

![Fig. 6](image)

Toads are often used as the feet of bronze wares

3.3 Toad Feet of the Seismoscope

The toad was always regarded as Luna in ancient China. Among historical relics from the late period of the Shang Dynasty (more than 3000 years ago) excavated in Sichuan, only the Sun-God and Luna, i.e., the Golden Crow and Golden Toad, were made with gold foil. In this way, the toad’s noble position may result from reproduction worship, sacrifices to beg for rain, and Luna worship and the like. Toad worship was very popular in the Han Dynasty, therefore, the toad was mostly drawn in the moon in murals, silk-cloth paintings and stone reliefs. The story about the Goddess Chang-É's flying to the moon is the most well-known myth in China (Fig. 5), so, toad sacrifice has become a Chinese tradition. Up to now, some minorities still pray for rain and celebrate their festivals with the toad.

The historical records describe the toad like this: “Underneath the vessel there were eight toads supporting the wine jar, so that they were ready to receive the ball if it should be dropped” and “Following the swing orientation of the jar, the lever released, the dragon instantly dropped the ball out of its mouth, and the toad which caught it in its mouth made a vigorous sound”, which indicates that the toad plays two roles, supporting the jar as the feet and accepting the dropping copper ball. In addition, the bumping sound of the ball can alert watchers to the occurrence of an earthquake. In fact, all vaulted jars in the Han Dynasty excavated up to now were constructed with their feet. The feet of bronze wares were very popular in China, and they were made into the
shape of a toad as well as a bear, tiger and tortoise in general cases (Fig. 6).

![Fig. 7](image)

**Fig. 7**

The restored model designed at the early stages, where toads bestrewn on the ground in all directions

(a) The first restored model proposed by Hattori in 1875;  
(b) The model proposed by Wang Zhenduo in 1951

However, the toads were bestrewn on the ground in eight directions in the early restored models (Fig. 7 (a)), which was handed down in some restored models in China (Fig. 7 (b)). However the toad as the vessel foot had ever been recorded in the newly-excavated historical materials. The archaeological survey for the Ling Observatory shows that the room for the seismoscope is only 2.3 meters wide, and there is indeed not enough space for toads to be bestrewn in all directions. The fault for the models restored at the early stages may be because researchers indiscriminately imitated western sculptures. We easily see its prototypes from formations of European and American sculptures (Fig. 8 and Fig. 9).

![Fig. 8](image)

**Fig. 8**

Latona Fountain in Versailles in 1689 in France, where toads were bestrewn in all directions

Fig. 10 shows the formation of the newly restored model, and the formation better lives up to characteristics of the historical records and excavations. This reflects the significance of ancient Chinese culture. Now we attach some characteristics for description as the following:
4 SCIENTIFIC TESTING

In a hydraulic lab, a strict professional experiment was done on the restored model in the original size (Fig. 11). The vibrostand can simulate all kinds of ground movement accurately under the control of the computer system. In the experiment, a series of parameters such as natural period, frequency response, load effect, rotational inertia, direction of reaction and displacement range were measured. Based on these parameters the interior structural details of the suspended structure of the general pillar design and mass distribution were improved. In order to test the response of the restored model to earthquakes, 14 real modern seismic recordings were tested reasonably (Fig. 12 shows only one of the cases of earthquakes) beside the application of the restored synthetic seismogram of the Longxi earthquake occurring in 134 A.D., of which the maximum acceleration and amplitude for the measured seismic seismogram fell within 10 gal and 4mm respectively. The restored model presented pretty good seismic testing results with stable repeatability, and there is no spurious triggering for non-seismic ground vibration. Thus, Zhang
Fig. 11
Seismological experiment on the vibrostand in a lab for the restored model in original size

Fig. 12
A case for testing: a digital seismogram in Xiaxian county
(The event: January 24, 2011, $M_s = 4.8$, $H = 12$ km, epicentral distance 54 km, a felt earthquake)

Heng’s seismometry thought is well proven in the experiment.

After the newly-restored bronze model was completed, it was exhibited in the China Science and Technology Museum, Henan Museum and Shanghai Science and Technology Museum in order for people to intuitively understand the working principle and interior structure of Zhang Heng’s seismoscope, in combination with the vibrostand for function demonstration of the instrument. The model is also cited in the *Encyclopedia of China* and textbooks of elementary and secondary schools.

4 CONCLUSIONS

Centennial restoration research of Zhang Heng’s seismoscope has witnessed a course of ceaseless pursuit, and embodies a human, scientific spirit to explore truth. In recent decades, new research achievements on historical materials, archaeology and historical seismology have been achieved in Chinese academic circles, which lay a good foundation for the establishment of the newly restored model. Not only does the new model more accord with historical materials, but can also detect earthquakes for the first time. The scientific research is endless, and later generations are expected to keep up with further research.
REFERENCES

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