Comparative analysis of strain parameter acquisition based on Cave strain and GPS observation

Leyin Hu\textsuperscript{1,3}, Taiwen Lv\textsuperscript{2}, Rui Yan\textsuperscript{1}, Zhiyong Fan\textsuperscript{1} and Bin Xu\textsuperscript{1}

\textsuperscript{1}Beijing Earthquake Agency, Beijing, China, 100080;
\textsuperscript{2}Shandong Shengfeite Steel Structure Corporation Limited, Liaocheng, China, 252131
\textsuperscript{3}Email: huleyin@bjseis.gov.cn

Abstract. A set of three-component extensometers are installed on the Xibozi Seismic Station in Yanqing District, Beijing. The layout of the extensometers is an isosceles triangle, and the observation is the amount of expansion and contraction of each side, which is then converted into the strain value of each side. In this paper, the regional crustal strain parameters were calculated based on the observations of the extensometers and the continuous GPS observations around Xibozi Seismic Station. From two aspects of observation at the same site and different scales, the ground strain information reflected by the two observation methods is compared and analyzed. From the strain parameters calculated by a single point (extensometers) and the strain parameters calculated by the triangular surface observation (GPS) with different specifications, the overall Beijing area is in the context of tensile strain. However, there is a gap of several orders of magnitude between the two results, which may be related to the artificial operation of the pre-processes such as zero drift and step removal of the instrument's strain observation data.

1. Introduction
In the observation of fixed-point crustal deformation, in order to describe the stress situation of the rock before and after the earthquake and monitor the change of the direction and rate of crustal movement, it can be achieved by observing the ground strain. At present, the strain technology methods used for earthquake precursor observation mainly include two types: cave strain observation and borehole strain observation. The object of the strain observation of the cave is the relative change of the horizontal distance between two base points in the cave with time, and it is one of the main methods of strain solid tide observation. The cave strain is mainly observed with an extensometer.

The study of cave strain in China began in the 1980s, and many scholars have done a lot of work in the theoretical research and application of obtaining the crustal strain solid tidal parameters using cave strain observation data [1-5]. Among them, Liu Xuyan et al deduced the geodetic coefficient and phase correction of the strained solid tide, and verified the theoretical value formula through the Venedikov harmonic analysis calculation. Then, using the strained solid tide data from three different directions in Guzan Station of Sichuan as an example, the method of calculating the magnitude of the main strain and the shear strain analysis of the direction machine based on the observation data of the strained solid tide from more than three different directions are discussed systematically [1-2]. Lv Pinji et al collected many observations related to cave strain observations in my country, summarized commonly used cave strain data processing methods, and counted whether the cave strain observations
were abnormal within a certain range near the epicenter before earthquakes. The statistical relationship between the anomaly and the epicenter and magnitude is obtained [6].

The strain observation of the Xibozi Cave in Yanqing officially began in 1987, and the current observation instrument is the SS-Y indium tile rod extensometer. Since its operation, the observation data produced by the instrument has a clear solid tide, and the annual change rule is relatively clear. The observation data is used in daily earthquake situation tracking and annual earthquake situation consultation work, which plays an important role in the analysis of deformation earthquake precursor anomalies in Beijing. The baseline of the Xibozi cave’s strain observation consists of a closed isosceles triangle, which is composed of three directions of EW (34 meters), NS (34 meters), and NE (48 meters). The crustal strain parameters calculated from the observation data can be Reflect the characteristics of strain changes in this area. However, due to its single station observation characteristics, it can only reflect single-point (local) deformation.

GPS observations can not only obtain information on the long-term changes in the crustal structure, but also capture transient micro-dynamic changes in the crust. At present, high-precision GPS has become an important technical means for studying horizontal crustal movement. Many scholars have used GPS observations to study the regional crustal horizontal movement and strain characteristics and fault zone activity habits [7-9]. Moreover, because the solution of GPS observation data is based on a unified global framework, it is more suitable for the analysis of regional relative motion. Its advantage is that it reflects the deformation characteristics of lines or areas. Any station in the observation network can be used to form line observations and areas of different scales to observe and calculate the strain characteristics of the regional crust on the line and surface.

In this paper, the comparative analysis of continuous strain and GPS observations is carried out for the strain observation of the Xibozi cave in Yanqing. Comparing the geostrain information reflected by the two observation methods from the two perspectives of co-site observation and surface observation at different scales, calculating the regional strain parameters at different scales and performing a relative analysis, allows to deepen the characteristics of the spatial and temporal changes of the regional strain and to understand and provide a reference for anomaly tracking and earthquake analysis in Beijing.

![Figure 1. The distribution map of Xibozi Seismic and GPS stations.](image-url)
2. Data and basic preprocessing
The data used in this article mainly includes the strain observation data of Xibozi cave in Yanqing and continuous GPS observation data around the Xibozi station. Considering the consistency with GPS data, the data period is from January 1, 2007 to December 31, 2017. The hourly and daily values are used for the strain observation data of the cave, and the daily values calculated by the 30-second sampling data are used for GPS observation. In order to ensure the quality of GPS observations, the comparative data in this paper uses data from GNSS reference stations in Beijing and surrounding areas. All the stations used are bedrock stations. However, the methods proposed in this paper are also applicable to the calculation of data from soil observation stations. Figure 1 shows the location of the Xibozi seismic station and continuous GPS stations in Beijing.

2.1. Extensometers data
The Xibozi Seismic Station is located in the south of Nanyuan Village, Badaling Town, Yanqing County, with an altitude of 640m. Located on the south side of the Yanqing Basin, there are four main active faults closest to the station: the northern margin of the Yanqing Basin, the Kangzhuang-Yanqing hidden fault, the Nankou hidden fault, and the Nankou piedmont fault. The station was built in 1982 and the three-way FSQ float water pipe inclinometer and SSY-2 quartz extensometer were installed at the end of 1986. Afterwards, it has undergone several instrument upgrades and renovations. The current strain observation instrument for the cave is the SS-Y indium tile rod extensometer. The instrument of the strain gauge of the cave is arranged in the cave of the Xibazi Seismic Station. The cave is 740m above sea level and the length of the pilot tunnel is 96m. The main hole is composed of three observation baselines forming a closed isosceles right triangle. The three sides are EW (34m), NS (34m), and NW-SE (48m).

The cave lithology is Jurassic tuff, covering a thickness of 46-108m, the daily temperature difference within the cave is less than 0.01℃, and the annual temperature difference is less than 0.05℃. The observation environment has no obvious interference sources, and it is one of the crustal deformation observation caves with the best observation conditions in the country. The basic data of the strain observation of the Xibazitai cave in Yanqing are complete, the observation quality and the quality of the observation technology system are good, the solid tide is clear, the earthquake reflection ability is strong, it has a good response to the earthquakes of magnitude 5 and above in North China, and the earthquakes of magnitude 7 and above in the world Have better co-seismic response.

In order to obtain the most accurate crustal deformation information, basic data preprocessing was performed on the strain observation data of the cave, including the removal of jump points, the zeroing of steps, the removal of sudden rise data caused by obvious rainfall and temperature, etc. The data curve after preprocessing is shown in Figure 2.

![Figure 2](image-url)
2.2. GPS data
There are more than 20 continuously operating GPS observation stations in Beijing and surrounding areas. Taking into consideration the site conditions of the Xibozi Seismic Station and the distribution of surrounding GPS observation stations, 6 GPS reference stations were finally selected to form 4 triangular observation networks of different specifications. To calculate the strain parameters, the six stations are: Hebei Chicheng Station (HECC), Beijing Yanqing Station (BJYQ), Beijing Shisanling Station (BJSH), Beijing Fangshan Station (BJFS), Beijing Gubeikou Station (BJGB) and Tianjin Jixin Station (JIXN), these six stations are all bedrock stations, ensuring the quality and reliability of the observation and calculation results. The distribution of the GPS stations is shown in Figure 1.

3. Strain parameter calculation of extensometer
The cave strain observation object is "the relative change of the horizontal distance between two points on the earth's surface with time", and the observed physical quantity is the horizontal line strain. Wu Kai et al gave the Practical calculation method for strain tide parameters of three-component cave strain [10]. The basic principle is to set the length between two points A and B on the horizontal plane in a specified direction in the cave. The measurement baseline of L is shown in Figure 3. By observing the change in distance $\Delta L$ between points A and B, the horizontal strain is determined as:

$$\varepsilon = \left( \frac{L' - L}{L} \right) = \frac{\Delta L}{L}$$

Where $\varepsilon$ is the linear strain, that is, the relative change in unit length; $L$ is the baseline length, that is, the initial distance between points A and B; $\Delta L$ is the distance between the two points after the change. Convention: Rock compression and linear strain are negative, and rock tension and linear strain are positive. That is: $\Delta L < 0$, $\varepsilon < 0$, $\Delta L > 0$, $\varepsilon > 0$.

![Figure 3. Schematic diagram of horizontal strain observation.](image-url)

The linear strain $\varepsilon$ is one of the three components of the strain tensor $\varepsilon$ on the free surface of the ground. When there are three linear strain measurements in different directions on the plane, the principal strain and its direction can be determined and the strain can be calculated from this the shear strain component in the tensor.

Equation (2) is a practical formula for calculating the principal strain and the direction of principal strain using the observed value of the cave body strain in a specific direction.

$$\begin{align*}
\varepsilon_1 &= \left( \varepsilon_{NS} + \varepsilon_{EW} \right) + \sqrt{\left( \varepsilon_{EW} - \varepsilon_{NS} \right)^2 + \left( \varepsilon_{NS} + \varepsilon_{EW} - 2\varepsilon_{NW} \right)^2} / 2 \\
\varepsilon_2 &= \left( \varepsilon_{NS} + \varepsilon_{EW} \right) - \sqrt{\left( \varepsilon_{EW} - \varepsilon_{NS} \right)^2 + \left( \varepsilon_{NS} + \varepsilon_{EW} - 2\varepsilon_{NW} \right)^2} / 2 \\
\theta &= \frac{1}{2} \arctan \left[ \frac{\left( \varepsilon_{NS} + \varepsilon_{EW} - 2\varepsilon_{NW} \right)}{\left( \varepsilon_{EW} - \varepsilon_{NS} \right)} \right]
\end{align*}$$

Where: $\varepsilon_1$ and $\varepsilon_2$ respectively represent the principal strain value, $\theta$ is the angle between the maximum principal strain $\varepsilon_1$ axis and the positive semi-axis, called the orientation angle of the maximum principal strain axis, and it is agreed that x is positive The angle $\theta$ of the half-shaft steering
axis is positive, and vice versa, the angle $\alpha$ is also agreed. Since the $\varepsilon_1$ axis and the $\varepsilon_2$ axis are orthogonal to each other, the orientation of the $\varepsilon_2$ axis is determined by the orientation of the $\varepsilon_1$ axis.

The principal strains $\varepsilon_1$, $\varepsilon_2$ and their orientation angle $\theta$ at any point in the crustal medium are strain invariants that are not related to the choice of the coordinate system and have nothing to do with the convention of the sign of the $\theta$ angle. The linear strain observations in any two orthogonal directions the sum of the values is also an invariant at this point. The invariant is equal to $\varepsilon_1 + \varepsilon_2$, which is the surface strain at this point. This property can be used to verify the reliability of the calculated principal strain.

4. GPS observation network and strain parameter calculation

In the case of small deformation, it can be considered that the earth is an elastic body whose medium is uniform and continuous, that is, the original point will not be torn into bright spots after deformation, and the original bright spots will not overlap into one point. Based on the above assumptions, it is possible to analyze the displacement and strain of a measurement area using the method of large topographic deformation measurement according to the theory of elasticity. Li Yan Xing et al gave the detailed methods and formulas for calculating strain parameters using GPS observations [11,12]. A plot not only rotates under the action of surrounding plates or plots, but also elastoplastic deformation occurs on its edges and inside. The overall rotation and internal deformation of the plot can be described by the plot's rotational strain equation (3).

\[
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z \\
\end{bmatrix} = r \begin{bmatrix}
-sin\phi cos\gamma & -sin\gamma \sin\phi & 0 \\
\sin\phi & -\cos\phi & 0 \\
0 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\end{bmatrix} + r \begin{bmatrix}
\varepsilon_e \\
\varepsilon_m \\
\varepsilon_n \\
\end{bmatrix} \begin{bmatrix}
(y - \gamma_0) \cos\phi \\
(y - \gamma_0) \\
0 \\
\end{bmatrix}
\]

(3)

Where $\omega_x$, $\omega_y$, $\omega_z$ are the strain tensors of the plot. According to the above formula combined with the least square method, the strain parameters of each GPS triangle can be calculated. The main calculation results include the first principal strain, the second principal strain, and the east-west direction. Strain, north-east strain, north-south strain, first shear strain, second shear strain, maximum shear strain, preferred strain azimuth, surface strain and other parameters, select the first principal strain, second principal strain, and shear strain here, It is advocated that several strain parameters such as strain azimuth angle and surface strain are used as the main analysis indicators, and used for the subsequent comparative analysis of the cavern strain solution parameters.

5. Primary analysis of strain parameters from extensometer and GPS

In this paper, the principal strains and principal strain direction angles obtained based on GPS and cave strain results are all in the form of daily or hourly time series. In order to facilitate the comparative analysis of the two results, the daily calculation results are used.

From the analysis of a single strain parameter, the strain parameter obtained based on the cave strain observation has poor stability and a large variation range. The strain parameter obtained by the GPS solution result is relatively stable, and there are several orders of magnitude difference between the two. It is difficult to make comparative analysis on the time series of a single strain parameter.

However, considering that the cave strain observations are points (local observations), and the GPS observations can be combined to form surface observations of different scales, which can reflect the strain state of different blocks. This topic considers the regional strain state reflected by the two results in terms of comparative analysis, the annual average results were taken to calculate the annual strain vector diagram. Figure 4 shows the annual average strain vector obtained from the cavern strain calculation results, and Figure 5 shows the partial annual average strain vector obtained from the GPS calculation results.

On the whole, the strain vector calculated by GPS and the strain vector calculated by cave strain observation have a high similarity. However, as the scale of GPS triangulation observation network expands, its strain state also changes to varying degrees. The strain vector calculated by the BJFS-BJSH-BJYQ triangle observation network with the smallest distance from the Xibozi station to the
nearest area is the most similar to the strain vector obtained from the cave strain. It also shows that there are certain differential strain characteristics in different regions. Analyzing the reasons for their differences should also be combined with the basic geological structure information in the region to carry out in-depth exploration.

Figure 4. The annual average strain vector obtained from the cavern strain results (2011-2017).

Figure 5. The annual average strain vector obtained from the GPS results (2017).

6. Conclusions
Based on the strain parameters calculated from the cave strain observation and GPS triangle combination observation, the strain characteristics are analyzed, and the conclusions are as follows:

(1) Judging from the strain parameters calculated from single point (cavern strain) and triangular surface observations of different specifications, the Beijing area is under the background of tensile
strain. This background of the strain state is consistent with the results of many studies [13, 14], which also verifies the correctness of the results calculated in this paper.

(2) From the results of the strain vector image, the strain parameters calculated by GPS triangular observation and the strain parameters obtained from the cave strain are similar on the whole, but there are several orders of magnitude difference between the two results. This result is related to the manual operation of the cave strain observation data during the preprocessing of instrument zero drift and step removal.

(3) The strain parameters obtained by different GPS triangle observation combinations are not the same as the strain parameters obtained by the cave strain result, and there are different differences (primary strain level and principal strain direction, etc.), but the overall strain state is similar. Among them, the surface strain parameters obtained by the BJFS-BJYQ-BJSH GPS combination with the smallest range from the west dial station are closest to the surface strain parameters obtained by the cave strain, indicating that the cave strain results mainly reflect the single point (local) deformation state, and Due to the existence of the same reference frame, GPS is more suitable for the analysis of relative motion in a large area, and its advantage lies in the degeneration characteristics of the response line or surface. Moreover, as the area of the triangle increases, the area covered increases the existence of fault factors. Considering that different triangle combinations span different faults; this different strain characteristic reflects different fault states. From another perspective, different combinations of triangles can be used to measure different fault motion states. The specific deformation differences require further analysis with detailed fault information.

(4) From the comparison of individual strain parameters such as principal strain, surface strain, and shear strain, there is a huge gap between the cave strain and the strain parameter calculated by GPS in terms of time series shape and amplitude. The GPS results are relatively stable, and the cave strain results are less stable, even with annual changes. The reason for this phenomenon is mainly due to the fact that the extensometer observation is highly sensitive to factors such as cave temperature, humidity, instrument observation system, and crustal stress changes. The strain parameters have unstable characteristics. However, GPS observation data (especially the data from the rock-based GNSS reference stations selected in this study) are less sensitive to the above interference factors, and the coordinate system obtained under the global framework is relatively stable, so the calculated strain parameters are also relatively stable, but long-term continuous observation can reflect the internal strain state of the observation area better.

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