Load calculation and effect of deformation observation around Mudanjiang seismic station

Jiye Li¹*, Liyan Qin², Longchen Ma¹ and Baojun Ma¹
¹ Heilongjiang Earthquake Agency, Harbin, 150090, China
² Harbin Emergency Rescue Support Center, Harbin, 150000, China
*Corresponding author’s e-mail: jiye_li@126.com

Abstract. With the acceleration of urbanization, the impact of human production and life on the earthquake observation environment is increasingly prominent. In order to study the influence of the construction of buildings (structures) around the observation station on the geophysical observation data, taking the deformation observation vertical pendulum tiltmeter and cavern strain gauge of Mudanjiang Seismic Station as examples, through field verification, inspection of instrument and equipment working state, environmental interference and meteorological factors, it was found that the construction time and direction of the southeast residential area of the observation station were related to the abnormal characteristics. In this study, based on the principle of superposition of normal concentrated force point load on the surface of semi-infinite body, the load change caused by the construction of station surrounding engineering was quantitatively calculated, and the influence degree of load was analyzed, which would provide support for further clarifying the interference source.

1. Introduction
The observation of crustal deformation can clearly record the small changes of crustal stress, which has a good response to the changes in the interior of the crust before the earthquake. However, due to the rapid economic development, urban construction is faster and the observation site is more seriously disturbed. Deformation observation is constantly affected by engineering construction, such as reservoir impoundment, high-rise building construction, workshop construction, etc.; in order to obtain complete and accurate earthquake precursor information reflecting fault movement, it is necessary to study the influence of large load around the site on the observation data.

In the aspect of the influence of load on deformation observation, many scholars have made a lot of attempts. Hu Weijian et al. (2002) used the classical Boussinesq solution of concentrated force acting on the surface of semi-infinite elastic body to quantitatively analyze and study the change of surface load in borehole strain measurement; Luo Mingjin et al. (2016)[3] proposed the theoretical model of the influence of ground load on stress-strain, and discussed the stress-strain of stratum self-weight and the borehole strain caused by it; Qiu Zehua (2004)[1] established a two-dimensional finite uniform load model, a three-dimensional concentrated load model and a three-dimensional finite line segment load model for interference factors such as rivers, lakes, warehouses and railways that affect deformation observation; Wan Dengbao et al. (1994)[5] studied the influence of train load on earthquake precursory observation through comparative observation of water level, earthquake measurement, water temperature, geoelectricity and other projects in the field; Li Zuning et al. (2007)[4] calculated the influence of a large container yard on the south vertical displacement of the...
short leveling deformation observation site near Tianma fault in Xiamen according to the principle of superposition of normal concentrated force on the surface of semi-infinite body. Both Mudanjiang vertical pendulum tiltmeter and cavern strain gauge have good annual variation law since the observation, but the northsouth curve of vertical pendulum began to accelerate southward tilt at the end of 2012 (Figure 1.); the eastwest curve of cave strain turned in April 2012, from the original compression trend to the expansion trend (Figure 2.). Through verification, it is found that during the abnormal curve period of Mudanjia ng vertical pendulum tiltmeter and cavern strain gauge, the instrument worked normally without obvious changes of meteorological factors such as air pressure, rainfall and temperature; the construction time of residential area in southeast direction of the station was consistent with this anomaly, and the direction was more consistent with the south tilt of vertical pendulum, so the interference caused by this can not be ruled out. In order to confirm whether the abnormal changes of the cavern strain gauge and vertical pendulum tiltmeter are related to the construction of nearby projects, it is necessary to carry out quantitative analysis on this interference factor. Therefore, based on the principle of superposition of normal concentrated force point load on the surface of semi-infinite body, the load change caused by the construction of station surrounding engineering was quantitatively calculated, and the influence degree of load was analyzed, which would provide support for further clarifying the interference source.

Figure 1. Long term curve of Mudanjia ng vertical pendulum

Figure 2. Long term strain curve of Mudanjia ng cavern
2. Survey of geological structure observation instruments at stations

Mudanjiang seismic station was founded in 1971, located in badagou, Mudanjiang city. It belongs to the national basic station. The station coordinates longitude: 129° 35′ 31″, latitude: 44° 36′ 59″, altitude: 250 m. The deformation observation site is located in the north of Changbai block, the secondary structure of Heilongjiang sub plate, at the intersection of Dunmi fault and Mudanjiang fault. It is an ideal geographical and structural location for the observation and study of subduction zone dynamics and deep earthquakes. The platform foundation is selected on the intact and large-scale exposed Proterozoic mixed granite (γ2). The rock is hard, dense, and basically free from weathering. Its joints are not well developed, and the integrity is good (Figure 3).

![Figure 3. Geological structure map of Mudanjiang seismic station](image)

The existing deformation observation means of Mudanjiang seismic station include: long water pipe tiltmeter, cavern strain gauge, volume strain gauge, gravity and vertical pendulum tiltmeter (see Table 1). In the early stage of the tenth five-year plan, a cave was purchased next to the earthquake measuring cave. The top of the cave is relatively flat and symmetrical, with vegetation coverage, and is an ideal deformation cave. The deformation observation is selected in the branch tunnel (not covered) of the cave, which is more than 28 m away from the entrance of the cave, and the covering thickness of the mountain body is not less than 30 m. The depth of the cave is 74.8 m and the covering thickness is more than 30 m. From the entrance of the cave to 42 m, the ground inside the cave is flat. It's not covered further than 42 m. The annual temperature in the cave is about 7.5 ℃. The humidity is about 80 % (Figure 4).

| Instrument name                      | Direction | Version | Manufacturer      | Quantity | Technical index | Recording mode        | Start observation time | Remark       |
|--------------------------------------|-----------|---------|-------------------|----------|-----------------|------------------------|------------------------|--------------|
| Vertical pendulum tiltmeter          | EW/NS     | VS      | Wuhan Institute   | 1        | 0.0002"         | Digital acquisition    | 2007.5                 | 15           |
| Water tube tiltmeter                 | EW/NS     | DSQ     | Wuhan Institute   | 1        | 0.0002"         | Digital acquisition    | 2007.5                 | 15           |
| Cavern strain gauge                  | EW/NS     | SS-Y    | Wuhan Institute   | 1        | 1x10-10         | Digital acquisition    | 2007.5                 | 15           |
| Borehole volume strain               | TJ-II     |         | Wuhan Institute   | 1        | 1x10-9          | Digital acquisition    | 2007.5                 | 15           |
| Broadband tiltmeter                  | EW/NS     | VP      | Wuhan Institute   | 1        | 0.0001"         | Digital acquisition    | 2014.8                 | Ambient field |

Table 1. Deformation observation instruments and equipment at Mudanjiang seismic station
Figure 4. Schematic diagram of Mudanjiang cave

3. Calculation method

3.1. Determination of Young's modulus and Poisson's ratio

Young's modulus is the physical quantity that characterizes the tensile or compressive strength of material within the elastic limit, which is the elastic modulus along the longitudinal direction. The absolute value of the ratio of transverse strain caused by uniformly distributed longitudinal stress to corresponding longitudinal strain is Poisson's ratio. Compared with the data of previous studies (Table 2 and Table 3), the approximate values are given. Young's modulus $E = 5.0 \times 10^{10}$ Pa and Poisson's ratio $\nu = 0.25$, which are used to estimate the load effect.

| Rock type          | $E(10^4\text{MPa})$ | $\mu$       |
|--------------------|---------------------|-------------|
| Diorite            | 10.1021—11.7565     | 0.26—0.37   |
| Fine-grained granite | 8.1201—8.2065   | 0.24—0.29   |
| Plagioclase granite | 6.1087—7.3984   | 0.19—0.22   |
| Porphyritic granite | 5.4938—5.7537   | 0.13—0.23   |
| Granodiorite       | 5.5605—5.8302     | 0.20—0.23   |
| Quartz sandstone   | 5.3105—5.8685     | 0.12—0.14   |
| Gneiss granite     | 5.0800—5.4164     | 0.16—0.18   |
| Syenite            | 4.8387—5.3104     | 0.18—0.26   |
| Schist             | 4.3298—7.0129     | 0.12—0.25   |
| Basalt             | 4.1366—9.6206     | 0.23—0.32   |
| Andesite           | 3.8482—7.6965     | 0.21—0.32   |
| Sericite shale     | 3.3677             |             |
| Granite            | 2.9823—6.1087     | 0.17—0.36   |
| Fine sandstone     | 2.7900—4.7622     | 0.15—0.25   |
Table 3. Poisson's ratio of rock and soil

| The type and state of the soil | Poisson's ratio |
|-------------------------------|-----------------|
| Gravely soil                  | 0.15—0.20       |
| Sandy soil                    | 0.20—0.25       |
| Silt                          | 0.25            |
| Silty clay                    |                 |
| Solid                         | 0.25            |
| Plastic                       | 0.3             |
| Flowing                       | 0.35            |
| Solid                         | 0.25            |
| Plastic                       | 0.35            |
| Clay                          |                 |
| Plastic                       | 0.35            |
| Flowing                       | 0.42            |

Note, Poisson's ratio of soil is difficult to obtain accurately, and the above is only an approximate value.

3.2. Effect calculation

According to the principle of superposition of normal concentrated force point load on the surface of semi-infinite body (Fu Rongshan et al., 2011)[2], the influence of engineering construction on the observation of cavern strain at Mudanjiang seismic station was calculated.

An arbitrary displacement field $u$ can be decomposed into non rotational and non-divergent displacement fields (Lay et al., 1995)[6];

$$ u = \nabla \Phi + \nabla \psi $$  \hspace{1cm} (1)

In the formula, the vector potential $\Phi$ and scalar potential $\psi$ can be expressed as the curl and divergence of another vector potential respectively, i.e.,

$$ u = - \nabla \times \varphi $$  \hspace{1cm} (2)

$$ \Phi = \nabla \cdot \varphi $$  \hspace{1cm} (3)

The Lamé equation, regardless of physical force, can be expressed as

$$ (\lambda + \mu) \nabla \theta + \mu \nabla^2 \mu = 0 $$  \hspace{1cm} (4)

In the formula, $\theta = \nabla \cdot \mu$  \hspace{1cm} (5)

By substituting equation (1) into equation (4) and making vector function $\zeta = \nabla^2 \varphi$, we can obtain the general solution of Neuber babokovich of lame equation (Wu Jialong, 2001):

$$ \mu = \zeta - \frac{1}{2 (1 - \nu)} \nabla (\Phi_0 + \frac{1}{2} r \cdot \zeta) $$  \hspace{1cm} (6)

$\Phi_0$ is a harmonic function and $r$ is a position vector. Because the problem of the surface of semi-infinite space under the action of normal concentrated force belongs to the space axisymmetric problem, the forms of $\zeta$ and $\Phi_0$ are $\zeta_1 = \zeta_2 = 0$, $\zeta_3 = \zeta_3 (p, z)$, $\Phi_0 = \Phi_0 (p, z)$.

In the formula, $p$ is the horizontal component; $z$ is the vertical component.
Therefore, the form of displacement component of equation (6) is

\[ \rho \mu_v = -\frac{1}{2(1-\nu)} \frac{\partial}{\partial \rho} \left( \Phi_0 + \frac{\zeta_3 z}{z} \right) \]  

(7)

\[ \omega = \zeta_3 - \frac{1}{2(1-\nu)} \frac{\partial}{\partial z} \left( \Phi_0 + \frac{\zeta_3 z}{z} \right) \]  

(8)

In the formula, \( \mu_v \) represents horizontal displacement and \( \omega \) represents vertical displacement.

Assuming that the semi-infinite space is affected by the normal concentrated force, and the coordinates are selected as shown in Figure 5. According to the dimensional analysis, the harmonic function \( \zeta_3 \) is the negative first power of the length coordinate, while the harmonic function is the zero power function of the \( \Phi_0 \) length coordinate.

\[ \zeta_3 = 4(1-\nu) \frac{K}{r}, \]  

\[ \Phi_0 = 2(1-\nu) C \ln (r + z), \]  

(9)

\[ r^2 = \rho^2 + z^2. \]

In the formula, K and C are undetermined coefficients. By substituting equation (9) into equation (7) and (8), according to the stress of the free surface is 0, i.e.,

\[ (\sigma_z)_{z=0} = 0 \]

\[ (\tau_{z\rho})_{z=0} = 0 \]  

(10)

Meanwhile, considering that the resultant force of normal stress on the horizontal plane with distance \( z \) from the surface is equal to the normal concentrated force \( F \), the undetermined coefficients K and C can be obtained, i.e.,

\[ K = \frac{(1+\nu) F}{2\pi E}, \]  

(11)

\[ C = \frac{(1+\nu)(1-2\nu)}{2\pi E}. \]  

(12)

The solution of displacement component can be obtained by substituting formula (11) and (12) into equation (9), and substituting the result of equation (9) into equation (7).

\[ \omega = \frac{(1+\nu) F}{2\pi E r} \left[ \frac{z^2}{r^2} + 2(1-\nu) \right] \]  

(13)

Because Young's modulus E and Poisson's ratio \( \nu \) have been determined, the influence of engineering construction at different distances from Mudanjiang deformation observation site on vertical displacement of Mudanjiang seismic station can be quantitatively calculated. Then the influence of
surrounding overall construction conditions on the direct deformation observation of Mudanjiang seismic station can be obtained by using the superposition of different point loads.

4. General situation of project construction and analysis of calculation results

4.1. General situation of project construction

After the implementation of anomalies on the spot, there was a lot of engineering construction phenomena in the southeast of Mudanjiang station in this abnormal change period. According to the survey and collection results of Mudanjiang Seismic Station on the surrounding construction situation and compared with the development information of Mudanjiang real estate network, it was found that the surrounding constructions were mainly three large-scale buildings (Table 4 for details). The completion time referred to in the table refers to the time when the community has the conditions for entering the house, rather than the main body capping time. Generally, the main body capping time is half a year to more than one year earlier than the completion and acceptance time.

Table 4. Investigation of three large real estate development projects

| Item               | Phase | On-Stream time | Completion time | Architectural scale | Remark       |
|--------------------|-------|----------------|-----------------|---------------------|--------------|
| Silver dragon bay  | I     | 2012.8         | 2014.8          | 63000               |              |
|                    | II    |                | 47000           |                     | Not started  |
| Holiday landscape  | I     | 2010.6         | 2010.11         | 29169               |              |
|                    | II    | 2010.9         | 2011.6          | 40401               |              |
|                    | III   | 2011.5         | 2011.11         | 40437               |              |
|                    | IV    | 2013.6         | 2014.6          | 83008               |              |
|                    | V     | 2014.5         | 2015.6          | 47822               |              |
| Dawning new town   | I     | 2009.3         | 2012.11         | 383000              |              |
|                    | II    | 2010.4         | 2011.11         | 173000              |              |
|                    | III   | 2010.4         | 2014.11         | 229000              |              |

Accordingly, we can know the load source time period of the development area near Mudanjiang seismic station (Table 5).

Table 5. Time statistics of surrounding load sources

| Load name               | Starting time | Ending time | Loading period |
|-------------------------|---------------|-------------|----------------|
| Dawning new town phase I| June 2009     | June 2010   | one year       |
| Dawning new town phase II, III | October 2010 | October 2011 | one year       |
| Silver dragon bay       | April 2013    | October 2013| half a year    |
| Holiday landscape       | June 2010     | October 2011| one year       |

4.2. Estimation of construction weight

According to the method of estimating the weight of stairs in the field of construction engineering, the weight of a building with 150 m² and 10 floors is estimated as follows: concrete: 150 × 0.2 (average slab thickness) = 30 m³, 30 × 2.4 T = 72 T; reinforcement: the reinforcement is 4T according to the general structure; column concrete: 0.5 × 0.5 × 3 = 0.75 root, 0.75 × 15 (15 columns on one floor) = 11.25 T; total: (72 + 4 + 11.25) × 10 = 872.5 T. Its weight is about 872.5 T. In other words, the total weight of a 1500 m² building is about 872.5 T (i.e., 0.5817 T per square meter). Then we can estimate the weight of the building according to the above method, if the total construction area of the community is known.

According to the data collected above, the variation of load around Mudanjiang seismic station = final load - original load = (final building area - original building area) × 0.5817 T/m² = (final building area - original building area) × 0.5817 T.
- floor area) × 0.5817 T/m² = (final building area) × (0.88 ~ 0.9) × 0.5817 T/m².
Among them, the coefficient of 0.88 ~ 0.9 is the statistical value of the whole development area (final building area - floor area) / final building area.
According to the general situation of the project given in Table 4, the influence of four construction projects (Figure 6) from 2009 to 2013 on the surrounding load of Mudanjiang seismic station was calculated, and the results were as follows (Table 6).

Table 6. Statistical table of calculation results of peripheral load influence

| Load name             | Starting time | Ending time | The effect of load centroid on deformation displacement | Maximum influence of load on deformation displacement |
|-----------------------|--------------|-------------|-------------------------------------------------------|-----------------------------------------------------|
| Dawnng new town phase I | June 2009    | June 2010   | 1.089 × 10⁻⁵ m                                        | 1.331 × 10⁻⁵ m                                       |
| Dawnng new town phase II,III | October 2010 | October 2011 | 1.143 × 10⁻⁵ m                                        | 2.167 × 10⁻⁵ m                                       |
| Dawnng new town       | June 2009    | October 2011 | 2.231 × 10⁻⁵ m                                        | 4.232 × 10⁻⁵ m                                       |
| Silver dragon bay     | April 2013   | October 2013 | 0.521 × 10⁻⁵ m                                        | 0.637 × 10⁻⁵ m                                       |
| Holiday landscape     | June 2010    | October 2011 | 0.642 × 10⁻⁵ m                                        | 0.762 × 10⁻⁵ m                                       |

Figure 6. Satellite map of Mudanjiang seismic station and surrounding construction buildings

4.3. Effect analysis
The original minute value data of vertical pendulum tilt in northsouth direction and eastwest direction of cavern strain at Mudanjiang seismic station were preprocessed, and the daily mean long-term curve was obtained by eliminating sudden jump, step and man-made environment interference. According to the daily mean value curve, the abnormal amplitude of vertical pendulum in northsouth direction and
eastwest direction of cavern strain was calculated, and compared with the load variation caused by construction by theoretical calculation (Figure 7 and Figure 8).

**Figure 7.** Comparison of cavern strain EW abnormal annual variation and surrounding load variation of Mudanjiang

**Figure 8.** Comparison of abnormal annual variation of vertical pendulum NS and surrounding load variation of Mudanjiang

Through theoretical calculation and practical comparison, the cumulative deformation displacement affected by four times of load was less than the normal annual variation of Mudanjiang cavern strain (Table 7), and the influence amount of load only accounted for 10-30% of the annual variation of cavern strain. It can be seen that the load construction around Mudanjiang station was not the main
factor for the abnormal deformation of the cavern strain in 2012 and 2013, which was more than twice of the normal annual variation. Similarly, the cumulative construction load around Mudanjiang station was not the main factor of annual variation of vertical pendulum since 2013.

Table 7. Comparative analysis of abnormal deformation variation and cumulative load influence

| Time       | Maximum influence displacement of cumulative load | Abnormal variation of cave body strain | Abnormal variation of vertical pendulum | Normal annual variation of tunnel body strain | Normal annual variation of vertical pendulum |
|------------|--------------------------------------------------|--------------------------------------|----------------------------------------|---------------------------------------------|---------------------------------------------|
| 2009-2010  | 1.331x10^{-5}                                    |                                      |                                        |                                             |                                             |
| 2010-2011  | 2.804x10^{-5}                                    |                                      |                                        |                                             |                                             |
| 2012-2013  | 7.1x10^{-5}                                      | 6.8x10^{-5}                          | 0.5x10^{-3}                            | 3.4x10^{-5}                                 | 0.15x10^{-3}                                |
| 2013-2014  | 0.762x10^{-5}                                    | 13.9x10^{-5}                         | 0.5x10^{-3}                            |                                             |                                             |
| 2009-2015  | 4.897x10^{-5}                                    |                                      |                                        |                                             |                                             |

5. Conclusions and discussion

(1) Through the establishment of theoretical model, quantitative analysis of the influence of load on strain observation can give preliminary quantitative results, but this method is more effective when the load is close to the strain observation or the load change is large. Because of the complex crustal structure, the assumed model is based on the spatial stress state of isotropic elastic body. The farther the distance or the smaller the load change, the worse the accuracy of the model.

(2) According to the calculation results of the theoretical model of the influence of load on deformation, the theoretical calculation value of the influence of the surrounding engineering construction of Mudanjiang seismic station on the cavern strain and vertical pendulum were far lower than that of the actual observation data. Therefore, the load construction around Mudanjiang station was not the main factor for the abnormal deformation of the cavern strain in 2012 and 2013, which was more than twice of the normal annual variation. Similarly, the cumulative construction load around Mudanjiang station was not the main factor of annual variation of vertical pendulum since 2013.

(3) The existing models only consider that the crust is a homogeneous medium, but the actual crustal structure is extremely complex, so further analysis and researches are needed.

Acknowledgment

This work was financially supported by Science for Earthquake Resilience (XH19011).

References

[1] Qiu Zehua.(2004) Theoretical Analysis of the Minimum "Quiet" Distance from the Borehole Strain Observation Point to the Ground Load Interference Source [J], Journal of Rock Mechanics and Engineering, 23(23):63-67.
[2] Fu Rongshan, Huang Jianhua.(2001) Geodynamics [M], Higher Education Press, pp.107-117.
[3] Luo Mingjin, Tang Juiuan.(2016) Calculation of Formation Strain and Stress by Four Component Borehole Strain Observation [J], Journal of Earthquake Engineering, 38(z1):8-15.
[4] Li Zuning, Wu Shaozu, et al.(2007) Using Point Load Method to Study Tianma Fault Crossing Short Leveling Anomaly Data [J], Seismic Research, 30(1):35-38.
[5] Wan Dengbao, Wang Jiabin, et al.(1994) Influence of Train Load on Some Precursory Observations [J], Earthquake, pp.91-94.
[6] Lay T, Wallace T C, Modern global seismology [M], Elsevier, 1995.