Detection of a half-microgal coseismic gravity change after the Ms7.0 Lushan earthquake

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Abstract: Because only a small near-field coseismic gravity change signal remains after removal of noise from the accuracy of observations and the time and spatial resolution of the earth’s surface gravity observation system, it is difficult to verify simulations of dislocation theory. In this study, it is shown that the GS15 gravimeter, located 99.5 km from the epicenter of the Ms7.0 Lushan earthquake on April 20, 2013 at 08:04 UTC +8, showed the influence of the earthquake from 2013-04-16 to 2013-04-26 after a time calibration, tide corrections, drift correction, period correction and relaxation correction were applied to its data. The post-seismic relaxation process of the spring in the gravimeter took approximately 430 minutes and showed a 2.5 \times 10^{-8} \text{ms}^{-2} gravity change. After correcting for the relaxation process, it is shown that a coseismic gravity change of approximately +0.59 \pm 0.4 \times 10^{-8} \text{ms}^{-2} was observed by the GS15 gravimeter; this agrees with the simulated gravity change of approximately 0.31 \times 10^{-8} \text{ms}^{-2}. The rate of the coseismic gravity change and the coseismic vertical displacement, as measured by one-second and one-day sampling interval GPS units, is also consistent with the theoretical rate of change. Therefore, the GS15 gravimeter at the Pixian Station observed a coseismic gravity change after the Ms7.0 Lushan earthquake. This and similar measurements could be applied to test and confirm the theory used for these simulations.

Key words: GS15 gravimeter; coseismic gravity change; the Ms7.0 Lushan earthquake

1 Introduction

A powerful earthquake always results in a change in the gravity potential field of the earth that can be observed as a small change in the local gravitational acceleration. Such coseismic gravity changes have been observed after the 1964 Mw9.2 Alaska earthquake by mobile relative gravimetry¹ and after the 1998 Mw6.1 earthquake near Iwate-san Mountain by absolute gravimetry². Recently, the coseismic gravity changes caused by powerful earthquakes (the 2003 Mw7.9 Tokachi-oki earthquake; the 2007 Mw9.3 Sumatra earthquake; the 2010 Mw8.8 Chile earthquake) have been acquired by high-precision, time-variable gravity measurements from networks of superconducting gravimeters and GRACE³,⁴. These measurements have been verified by simulations based on finite rectangular dislocation theory and the local layered wave velocity structure of the crust and upper mantle, which calculate the surface coseismic and post-seismic gravity changes⁵. There are several difficulties in validating the accuracy of these simulations using the current observation system, including the low precision and low temporal resolution of both the vertical displacement measured by GPS and the
time-variable gravity measured by GRACE. These are largely inadequate to use at high temporal resolution for checking the fast coseismic gravity changes that occur during earthquakes. Furthermore, due to the powerful shock of earthquakes, there are few near-field, ground-based gravimeters that can confirm the existence of physical phenomena suggested by observations of coseismic gravity changes.

On April 20, 2013 at 08:02:46 UTC +8, a Ms7.0 (Mw6.6) earthquake occurred in Lushan, in the Sichuan Province. The GS15 gravimeter located approximately 99.5 km from the epicenter, at the Pixian seismic station, captured a complete record of the earthquake at a one-minute sampling interval. In this study, we analyzed the seismic record from April 16 to 26 and applied time calibrations, tide and drift corrections and corrections by period and relaxation analysis. The gravimeter data were used to check and confirm the near-field coseismic gravity change occurring as a result of the Ms7.0 Lushan earthquake.

2 Data processing methods

The gravity data were sampled at one-minute intervals by the GS15 gravimeter at the Pixian seismic station. The data were influenced by changing air pressures and solid tides but reflect timing errors from the data acquisition system, errors in the residual diurnal and semidiurnal wave signals corrected by tide theory, drift of the spring in the gravimeter, coseismic gravity changes and post-seismic relaxation effects. To simulate these error sources, the following model is used:

\[ g_{m}(t_i) = d_0 + d_1 t_i + \sum_{j=1}^{N_d} \left[ a_j \cos \left( \frac{2\pi}{T_j} t_i \right) + b_j \sin \left( \frac{2\pi}{T_j} t_i \right) \right] + \sum_{j=1}^{N_d} g_j H(t_i - T_{g_j}) + \sum_{j=1}^{N_s} k_j H(t_i - T_{s_j}) t_i + \sum_{j=1}^{N_s} k_j \exp \left[ - (t_i - T_{s_j})/\tau_j \right] H(t_i - T_{s_j}) t_i + v_i \]

Here, \( t_i \) for \( i = 1 \cdots N \) are the time intervals in units of minutes, \( g_{m}(t_i) \) is the residual gravity corrected by tidal theory, \( H \) is the Heaviside step function, \( d_0 \) and \( d_1 \) are the constant and linear terms of the residual gravity field, respectively, and the coefficients \( a_j \) and \( b_j \) describe the residual diurnal and semidiurnal wave signals of the residual gravity, respectively. The next term corrects for any number \( N_d \) of offsets that have magnitudes \( g \) and intervals \( T_{g_j} \). The post-seismic gravity change is modeled as a rate of change \( h_{t_i} \) and an exponential decay with magnitude \( k_j \) over the selected earthquake time intervals \( T_{g_j} \) and \( T_{s_j} \). The measurement errors \( v \) are initially assumed to be independent, identically distributed and random, with \( E(v) = 0 \).

The p-wave arrival time (2013-04-20 08:03:04.67 UTC +8) identified in the Pixian Station seismometer record is used to calibrate the site’s GS15 gravimeter. Several years of synthetic tides are determined from this gravity data record. An automatic pikes processing method is used to correct the sudden jumps in signal caused by the electronics and the far-field earthquake. The tidal, air pressure, drift and period corrections and the residual gravity are shown in figure 1.

Gravimeter records are susceptible to spurious signals from the step and sticking bar; these signals can strongly influence the long-term drift behavior. Figure 1 shows that the GS15 gravimeter has no such instrumentation problems. After subtracting the influence of the gravity tide ( \( \pm 200 \times 10^{-8} \text{ ms}^{-2} \) ), the drift of the spring ( \( -100 \times 10^{-8} \text{ ms}^{-2} \) ) and the air pressure ( \( \pm 4 \times 10^{-8} \text{ ms}^{-2} \) ), a gravity anomaly of approximately \( (3-4) \times 10^{-8} \text{ ms}^{-2} \) remains in the period correction before and after the Ms7.0 Lushan earthquake. The period correction comprises the error in the time system, the synthetic tide model, the coefficient of the scale factor, the nonlinear drift of the spring and the influence of the earthquake.

3 Calculation and analysis of the coseismic gravity changes

When the spring in the GS15 gravimeter receives seismic waves, the original dynamic equilibrium of the spring suddenly breaks, and the spring undergoes a relaxation process. In this study, the relaxation process is simulated with the exponential portion of equation 1. This relaxation analysis, shown in figure 2, finds an optimal \( \tau \) of 430 minutes and a residual error of approximately \( 0.40 \times 10^{-8} \text{ ms}^{-2} \).
Figure 1  The tidal, air pressure, drift and period corrections for the GS15 gravimeter at Pixian (The pressure admittance is $-3.79 \times 10^{-8}$ mbar. Over the 10-day period, the pole tide is linear)

Using the relaxation time (430 minutes) and the p-wave arrival time (2013-04-20 08:04:00) as constraints, the entire coseismic and post-seismic processes observed by near-field ground-based gravimeters are simulated from the residual gravity record from April 16 to 23, which is shown in figure 3. The post-seismic relaxation process indicated by the springs of such gravimeters is approximately $+2.5 \times 10^{-8}$ ms$^{-2}$. The post-seismic gravity change exhibits a negative trend, as before. The coseismic gravity change is approximately $(0.59 \pm 0.40) \times 10^{-8}$ ms$^{-2}$

Figure 2  The relaxation time fitting result for the Lushan earthquake observed at Pixian

Figure 3  Coseismic gravity change in the Lushan earthquake at Pixian (The blue line is the gravity change at Pixian Station, the magenta line is the relaxation process and the red line is the simulation result for the coseismic gravity change in the Lushan earthquake at Pixian Station)
for the Lushan earthquake observed at Pixian.

The coseismic vertical displacement measured by high-frequency GPS and gravity changes measured by the GS15 gravimeter during the earthquake (from 2013-04-20:08:00 to 08:06:37 UTC +8) are shown in figure 4. These two measurements sample the same region. The coseismic vertical displacement is approximately \(-1.1 \pm 2.1\) mm, as determined by piecewise polynomial fitting.

The statistics of the coseismic gravity change measured by the GS15 gravimeter, the simulated gravity change, and the vertical displacements of the GPS with sampling intervals of one day and one second are shown in table 1. The coseismic gravity changes from the GPS measurements with a theoretical gravity gradient of \(-300 \times 10^{-8} \text{ms}^{-2} \text{m}^{-1}\) are approximately 0.33 to 0.63 mm. Table 1 shows that both the ground-based coseismic gravity change and the simulated gravity change are approximately \(0.5 \times 10^{-8} \text{ms}^{-2}\) in the Pixian region after the Ms7.0 Lushan earthquake. In cases where the observed value and the precision are of similar magnitude, we used the vertical displacement of the one-second sampling interval GPS because its precision is higher than that of the daily sampling interval GPS. The vertical displacement changes exhibit negative trends, while the simulated coseismic gravity change and that observed by the GS15 gravimeter both exhibit positive trends. The coseismic gravity change observed by the GS15 gravimeter shows local changes, while the simulation captures the regional change. Including the coseismic gravity change indicated by the GPS measurements using the theoretical gravity gradient, all gravity changes are approximately \(0.5 \times 10^{-8} \text{ms}^{-2}\). Thus, the GS15 gravimeter at Pixian detected a half-microgal coseismic gravity change after the Ms7.0 Lushan earthquake.

![Figure 4](image-url)

**Figure 4** Coseismic vertical displacement and gravity changes from high-frequency GPS and the GS15 gravimeter for the same region as shown in figure 3 (The blue line is the vertical displacement indicated by the 1 Hz GPS during the Lushan earthquake, the black line is the model of the coseismic vertical displacement indicated by the 1 Hz GPS, the red line is the model of the coseismic gravity, and the magenta line indicates the occurrence time of the Ms7.0 Lushan earthquake).

**Table 1** Statistics of the coseismic gravity and displacement changes of the Ms7.0 Lushan earthquake, as measured at Pixian Station.

<table>
<thead>
<tr>
<th>Observation type</th>
<th>Longitude (°E)</th>
<th>Latitude (°N)</th>
<th>Sampling interval (second)</th>
<th>Coseismic vertical displacement (mm)</th>
<th>Coseismic gravity change ((10^{-8} \text{ms}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>value precision</td>
<td>value precision</td>
</tr>
<tr>
<td>GPS</td>
<td>103.7</td>
<td>30.9</td>
<td>1</td>
<td>(-1.1) ± 1.40</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>86400</td>
<td>(-2.1) ± 3.11</td>
<td>0.63</td>
</tr>
<tr>
<td>GS15</td>
<td>103.8</td>
<td>30.9</td>
<td>60</td>
<td>–</td>
<td>0.59 ± 0.40</td>
</tr>
<tr>
<td>Simulation result</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Note: The coseismic gravity change with the dislocation model of the earthquake source is simulated by the fault model used in seismic wave inversion offered by Institute of Geophysics, China Earthquake Administration\(^{10}\). Following the assumption that coseismic gravity changes are caused entirely by vertical displacement, the simulation of the gravity changes from the GPS data uses a gravity gradient of \(-300 \times 10^{-8} \text{ms}^{-2} \text{m}^{-1}\).
4 Conclusion and discussion

This paper demonstrates that the drift of creep characteristics can be corrected not only by a time system calibration and the traditional correction method\(^{[12]}\), but also by a conducting period and relaxation analysis of the spring gravimeter. The traditional method finds that the residual gravity change is approximately \(\pm 1 \times 10^{-8}\) ms\(^{-2}\). Simulated with the Heaviside step function and a relaxation function, the coseismic gravity change measured by the GS15 gravimeter is \((0.59 \pm 0.40) \times 10^{-8}\) ms\(^{-2}\), which agrees with the one-day and one-second time interval GPS records for the same region. The data record of the GS15 gravimeter at the Pixian Station is sensitive to a number of factors related to drift, solid earth tide and air pressure and is also affected by a number of important and inevitable error sources, such as error in the time system, the synthetic tide model, the coefficient of the scale factor and the nonlinearity of the spring drift. The period correction shows that there was a \((3 - 4) \times 10^{-8}\) gravity anomaly before and after the Ms7.0 Lushan earthquake. After the earthquake, the residual gravity took approximately 430 minutes to relax to a gravity change of approximately \(2.5 \times 10^{-8}\) ms\(^{-2}\). With both periodic and relaxation corrections, a coseismic gravity change of \((0.59 \pm 0.40) \times 10^{-8}\) ms\(^{-2}\) was recorded at Pixian by the GS15 gravimeter during the Ms7.0 Lushan earthquake.

The simulated coseismic gravity change, as well as the change measured by the GS15 gravimeter, was approximately \(0.5 \times 10^{-8}\) ms\(^{-2}\). The coseismic vertical displacements simulated with one-day and one-second time interval GPS records were approximately \(-1\) to \(-2\) mm. The ratio of the coseismic gravity change to the vertical displacement is consistent with the theoretical ratio. In conclusion, the GS15 gravimeter at the Pixian station detected a half-microgal coseismic gravity change in the Ms7.0 Lushan earthquake, and the dislocation model can be validated with this method in the future.

References