The Gravity Method and Interpretive Techniques for Detecting Vertical Crustal Movements [1]

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Observations of temporal variations of gravity can be used as an inexpensive and rapid means of detecting, monitoring, and studying crustal deformation associated with many active geologic processes. Such observations can yield qualitative or semi-quantitative information on elevation changes and, when combined with independent elevation data, can yield information about changes of the subsurface density field arising from both subsurface displacements and temporal variations of the density of materials in the subsurface. The effectiveness of gravity techniques in specific cases of crustal deformation depends on the configuration of the local gravity field, the physical processes involved in the deformation, and the accuracy with which temporal gravity variations can be measured.

Assuming that the effects of earth tides, and variations in atmospheric pressure have been removed, gravity measured at a fixed point on the surface of the earth can vary with time as a result of two factors: (1) displacement of the observation point along the free-air gravity gradient and (2) variation of the subsurface density field. Generally, both factors result in gravity variations of a few microGals per centimeter of vertical displacement. The normal vertical gradient of gravity is approximately -3.09 μGal/cm whereas the actual free-air gradient typically may differ from this value by ±5% and in special situations may differ by more than 15% (Hammer, 1970). Gravity changes caused by variations in the subsurface density field accompanying deformation may enhance, subdue, or dominate gravity changes resulting from vertical displacement, and the relation between gravity change and elevation change, $\Delta g/\Delta h$, may assume a wide range of values.

Some possible relations of gravity change and elevation change have been derived on the basis of theoretical considerations. The values of $\Delta g/\Delta h$ discussed below are based on simple crustal models and are presented primarily to illustrate the possible variability in $\Delta g/\Delta h$ for different geologic processes. All values include both the effect of vertical displacement along a normal free-air gradient and the effect of changes in the subsurface density field.

In a numerical model study of a dilating sphere buried in a homogeneous elastic half-space, Rundle (1978) found Δg proportional to Δh and the ratio $\Delta g/\Delta h$ equal to -3.1 μGal/cm. For this model, the gravity change is equal to the free-air effect due to uplift. If the increased volume in this model were partially or completely filled with water, $\Delta g/\Delta h$ would be slightly smaller. In the same study Rundle found that Δg caused by thrust movement on an infinitely long dipping fault buried in a homogeneous elastic half-space also was proportional to Δh. For a medium with density $\rho = 2.8$ g/cm^3, $\Delta g/\Delta h$ is equal to -1.9 μGal/cm or equivalent to the free-air effect due to uplift plus the gravity effect due to mass added to the vertical section, as Barnes (1966) proposed.

In a simple model of a homogeneous elastic plate of rectangular cross section and infinite length and subject to uniform horizontal compression or extension, Δg again is proportional to Δh. In this case, the gravity changes due to changes of elevation and changes in subsurface density field are nearly equal and tend to cancel. Thus the value of $\Delta g/\Delta h$ is approximately 0 μGal/cm. Numerical calculations of deformation and gravity change resulting from surface loads applied to radially symmetric, elastic earth models (Farrell, 1972) show a $\Delta g/\Delta h$ value near -2.3 μGal/cm.

When deformation is associated with processes dominated by fluid movement such as magma movement in volcanic areas or ground-water movement in areas subject to ground-water extraction, possible values of $\Delta g/\Delta h$ cover a wide range. The wide range is due in large measure to the range of subsurface volume changes possible in response to changes in pore pressure. For example, in some areas ground-water extraction is not accompanied by any appreciable subsidence of the surface whereas in other areas the removal of ground water appears to be accompanied by almost a complete collapse of the resulting voids (Poland and Davis, 1969). Furthermore, in some areas, a certain amount of ground water can be extracted before appreciable subsidence begins (Riley, 1970). Here, the relation between Δg and Δh probably would be nonlinear. Analogous behavior can be expected in volcanic areas.

$\Delta g/\Delta h$ relations measured in a limited number of cases are in general agreement with the model results, although excep-

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tions do exist. Barnes (1966) and Oliver et al. (1975) remeasured gravity in regions that had undergone deformation associated with slip on subsurface faults. Barnes found that many observations of $\Delta g/\Delta h$ in southern Alaska fell close to a value of -1.97 μGal/cm whereas $\Delta g/\Delta h$ values at stations along a profile extending northeast from Valdez were closer to the normal free-air gradient. An anomalous value of $\Delta g/\Delta h$ was found near Anchorage, an area in which a very small gravity change was associated with nearly 1 m of subsidence. Oliver and his coworkers determined a value of -2.15 ± 0.26 (s.d.) μGal/cm associated with deformation accompanying the 1971 San Fernando, California earthquake. Jachens et al. (1976) found a very good correlation between gravity changes and elevation changes that occurred during the November 1975 deflation of Kilauea Volcano, Hawaii. There, $\Delta g/\Delta h$ equaled -1.71 ± 0.05 (s.e.) μGal/cm. W. E. Strange and D. G. Carroll (W. E. Strange, written comm., 1977) studied the relation between gravity change and elevation change resulting from ground-water extraction in the San Joaquin Valley of California. They found a $\Delta g/\Delta h$ value near -3.0 μGal/cm in areas where water was withdrawn from confined aquifers, but a simple relation did not exist in areas where water was extracted from unconfined aquifers. Isherwood (1977) reported gravity changes and subsidence over a producing geothermal field at The Geysers, California. He found a $\Delta g/\Delta h$ relation of about 2.5 μGal/cm, indicating that gravity changes due to loss of fluid from the subsurface were larger than those due to vertical displacement.

Measurements of gravity change and elevation change have been reported that do not fit the simple models discussed above. Kisslinger (1975) reported that $\Delta g/\Delta h$ values of -3.7 μGal/cm and near -10 μGal/cm accompanied some phases of the Matsushiro, Japan earthquake swarm. Fujii (1976) discussed repeated gravity surveys before and after the 1973 Nemuro-hento-oki earthquake in southeastern Hokkaido, Japan. Coseismic and postseismic gravity changes were as large as 400 μGal. No values were given for the associated elevation changes, but they were described as being too small to affect the observed gravity values. In another area of Japan, the Muira Peninsula, which was uplifted 1-2 m during the 1923 Kanto earthquake, repeated gravity and leveling surveys conducted since 1955 have shown the expected inverse correlation between gravity change and elevation change (Hagiwara, 1974). However, the gravity changes are about ten times larger than expected. These results may be slightly affected by ground-water fluctuations beneath the reference station at Tokyo.

On the basis of the above discussion, some general statements can be made about temporal variations of gravity as related to crustal deformation. First, gravity changes accompany most types of deformation, and a knowledge of such changes can yield information about the spatial distribution of the deformation. Second, unambiguous estimates of elevation changes are not possible on the basis of gravity data alone. Third, in some situations (for example, San Fernando, California and Hawaii), the measurements of Δg and Δh at a few locations may permit the determination of $\Delta g/\Delta h$ that then can be used to infer elevation changes from measured gravity changes. Finally, the wide range of possible values of $\Delta g/\Delta h$ shows that, in some cases, observed values of this relation can effectively constrain the interpretation of the causes of the deformation.

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